PHOTONICS RESEARCH GROUP

Novel Materials and Integration Technologies for Silicon Photonics

Dries Van Thourhout / September 2020

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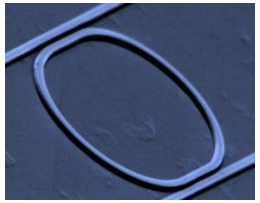
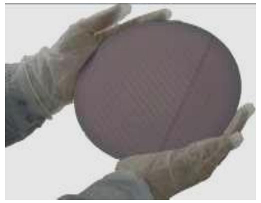
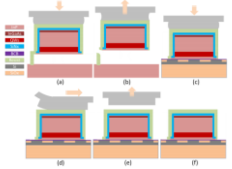
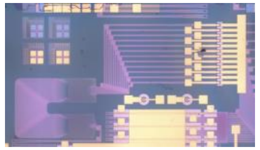
Photonics Research Group









Research Group of Ghent University

- Faculty of Engineering and Architecture
- Department of Information Technology (INTEC)
- Associated laboratory of IMEC
- Member of the Center for Nano- & Biophotonics (NB photonics)

Technology Research

- Photonic Integration: Systems on a chip
- On silicon: “Silicon Photonics”
- Enhanced with new materials:
  III-V, ferro-electrics, graphene, …

Applications

- High-speed telecom and datacom
- Sensing for life sciences: visible and Mid-IR
- Optical information processing

9 Professors
16 postdocs
50 PhD students
10 support staff

20+ nationalities
6 ERC grants
6 spin-off companies
50 journal papers/year
Class 100 clean rooms
M.Sc. Photonics program

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PROFESSORS

Group

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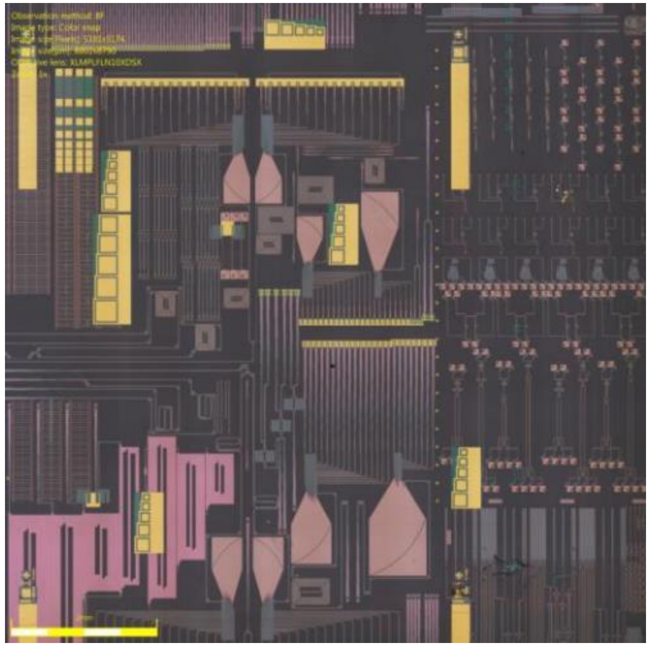
Common Theme: silicon photonics?

The implementation of high density photonic integrated circuits by means of CMOS process technology in a CMOS fab



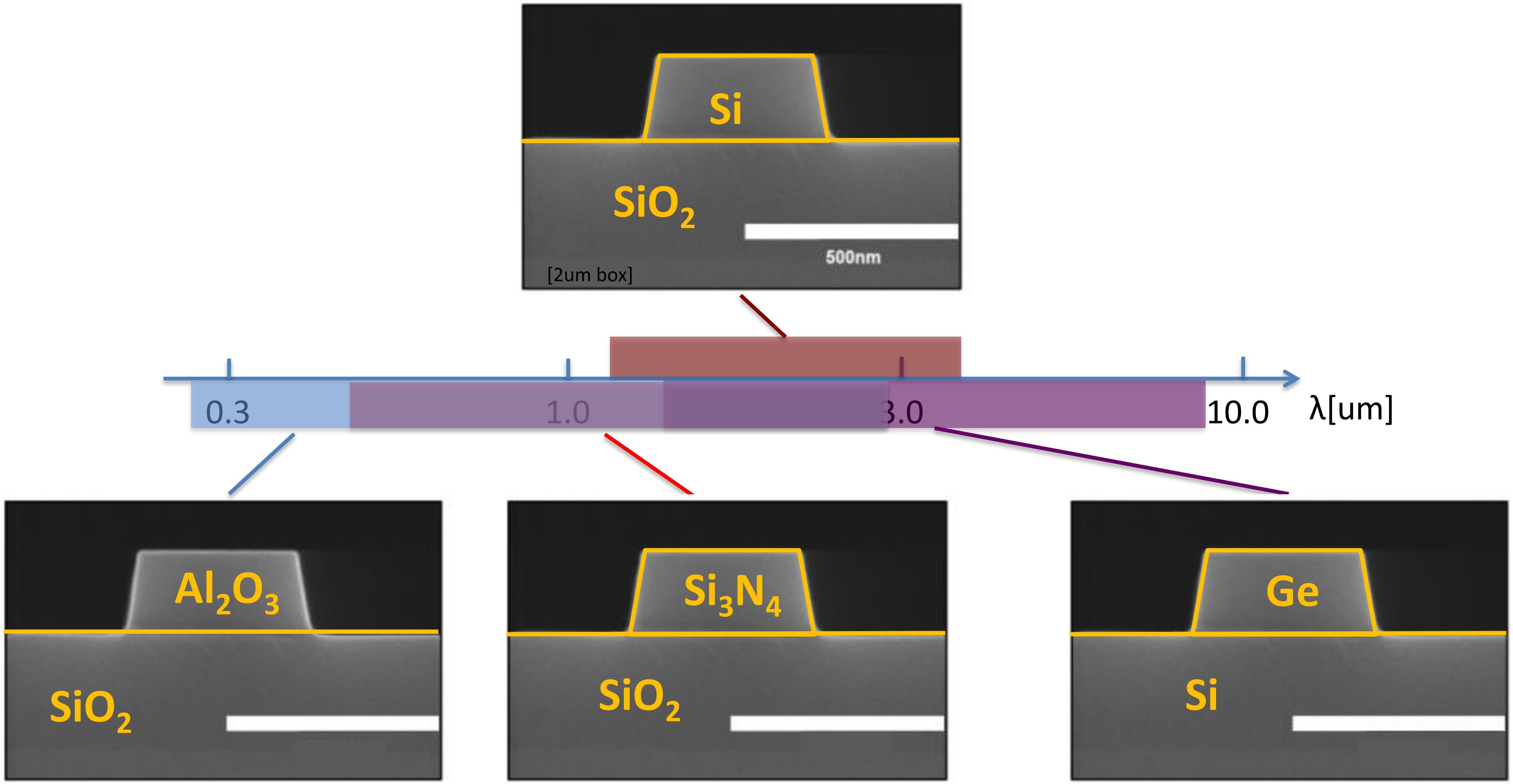


Pictures, courtesy of imec

Enabling complex optical functionality on a compact chip at low cost

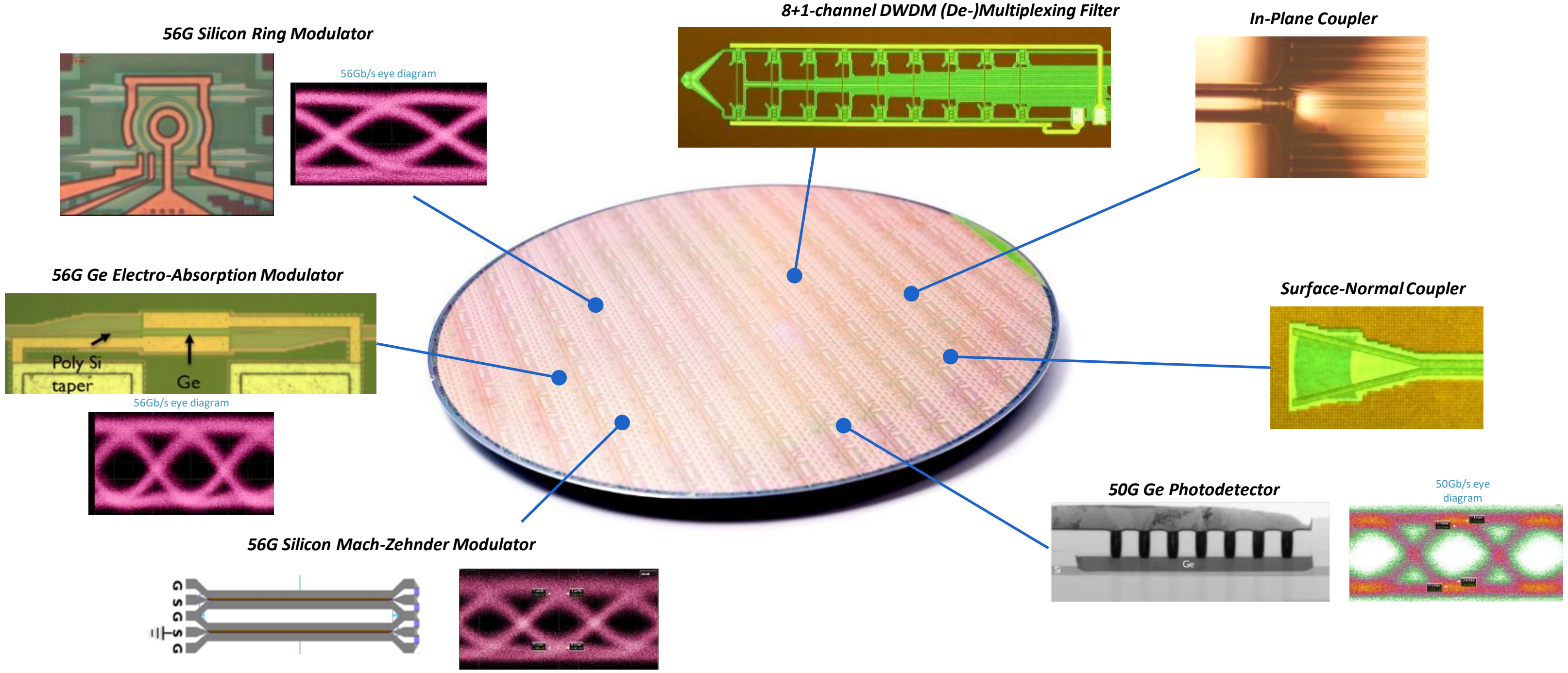
Silicon Photonics: Our Waveguide(s)

… without leaving the CMOS fab



IMEC SILICON-ON-INSULATOR PLATFORM

Fully Integrated 8x56G DWDM Si Photonics Technology



Co-integration of the various building blocks in a single platform

Today available on 200mm wafer size, coming soon on 300mm

95% compatible with CMOS130 in commercial foundries

NEED FOR NOVEL MATERIALS

Silicon is great but:

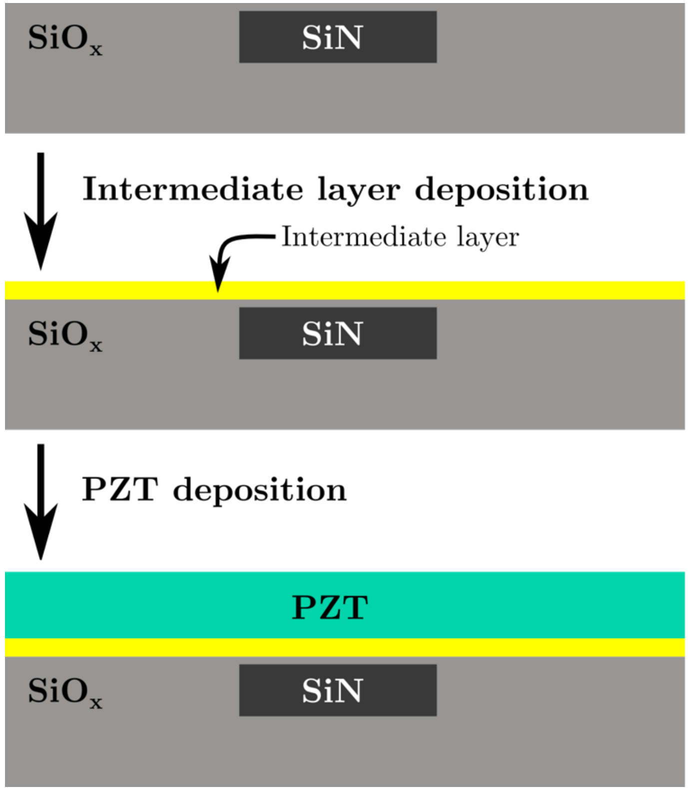
- Indirect bandgap: no efficient light emission
- Cubic lattice: no second order non-linearities, no electro-optic effect

Hence need for integration with new materials:

- **Ferroelectrics** (PZT, BTO) for phase modulators and SHG
- **Graphene** and other **2D-materials** for intensity and phase modulators
- **Colloidal quantum dots** for light sources and single photon emitters
- Direct bandgap **III-V semiconductors** for efficient light emission

FERRO-ELECTRIC MATERIALS ON SILICON

Developed new process to deposit BTO, LN, PZT on any substrate

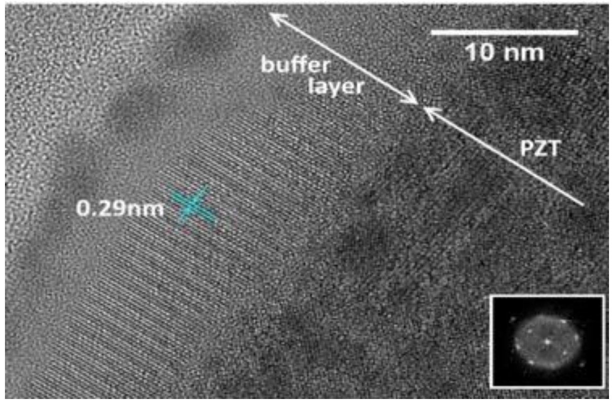


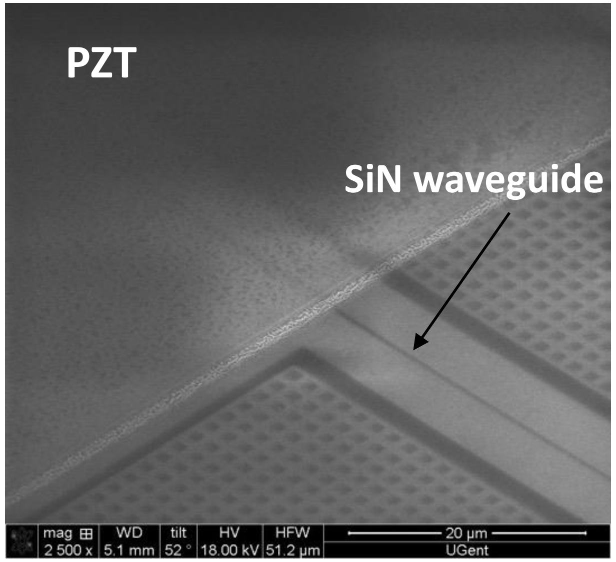
Lanthanide buffer layer

(10-20 nm)

PZT sol-gel deposition

(@ 500-600°C)





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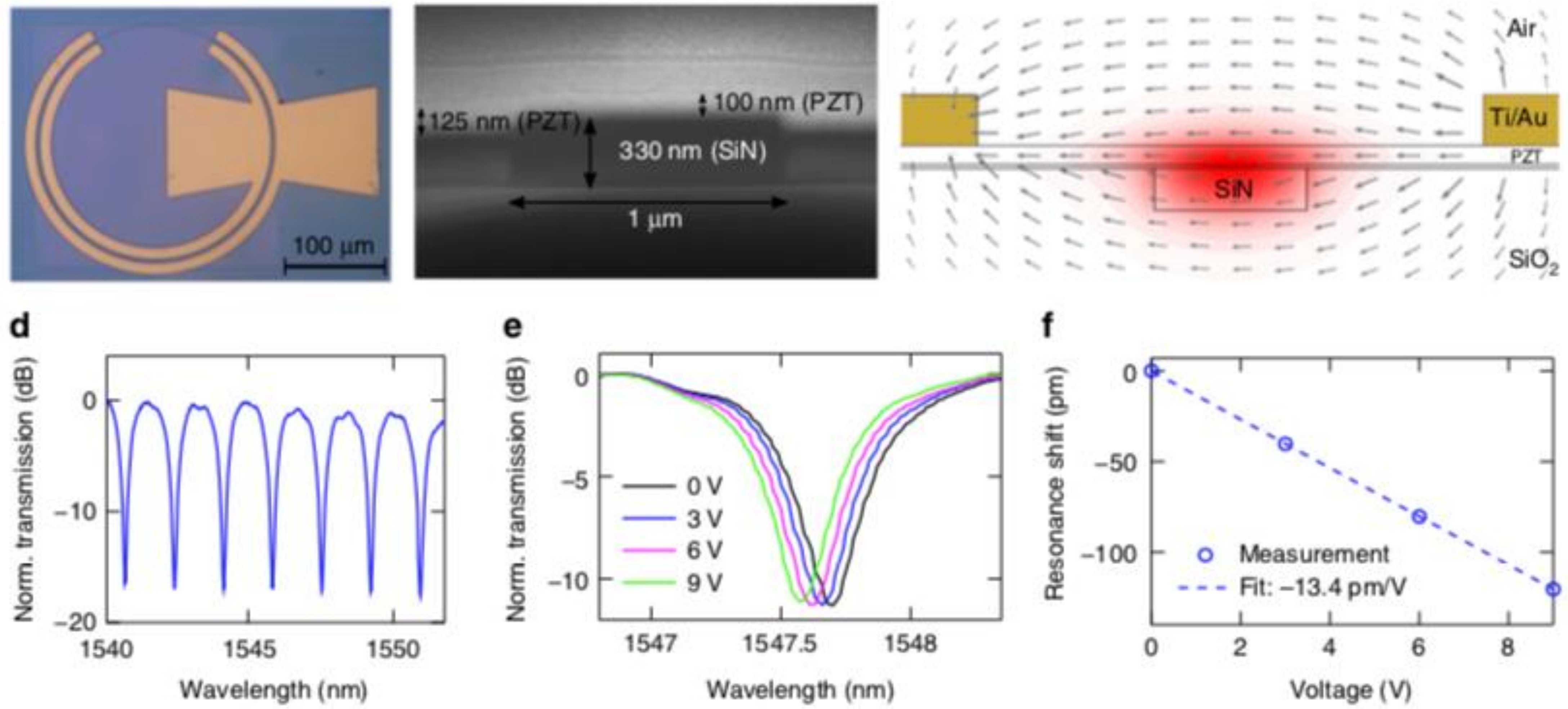
More information: George, J. P., et al. ACS applied materials & interfaces (2015)

ELECTRO-OPTIC MATERIALS ON SILICON

PZT by spin coating



K. Alexander, Nature Communciations 2018

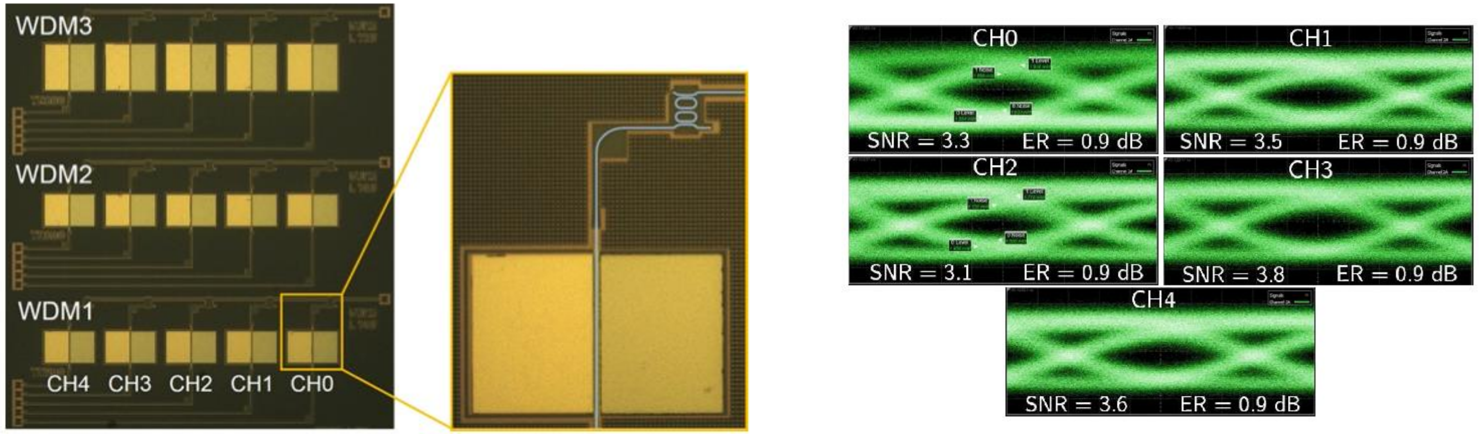
Collaboration J. Beeckman (LCP, UGent)

2D MATERIALS ON SILICON

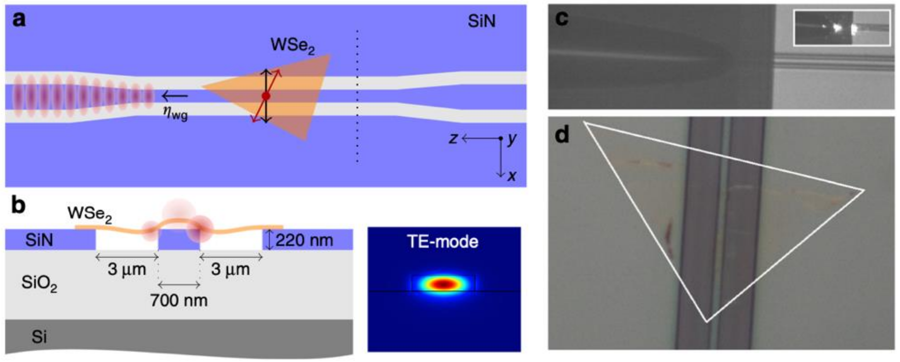
Demonstrated high-speed graphene EA-modulators

Demonstrated single-photon emission from WSe_2 coupled to SiN-WG

Exploration of novel 2D-materials for phase modulation



C. Allessandri e.a. , Applied Optics 2019



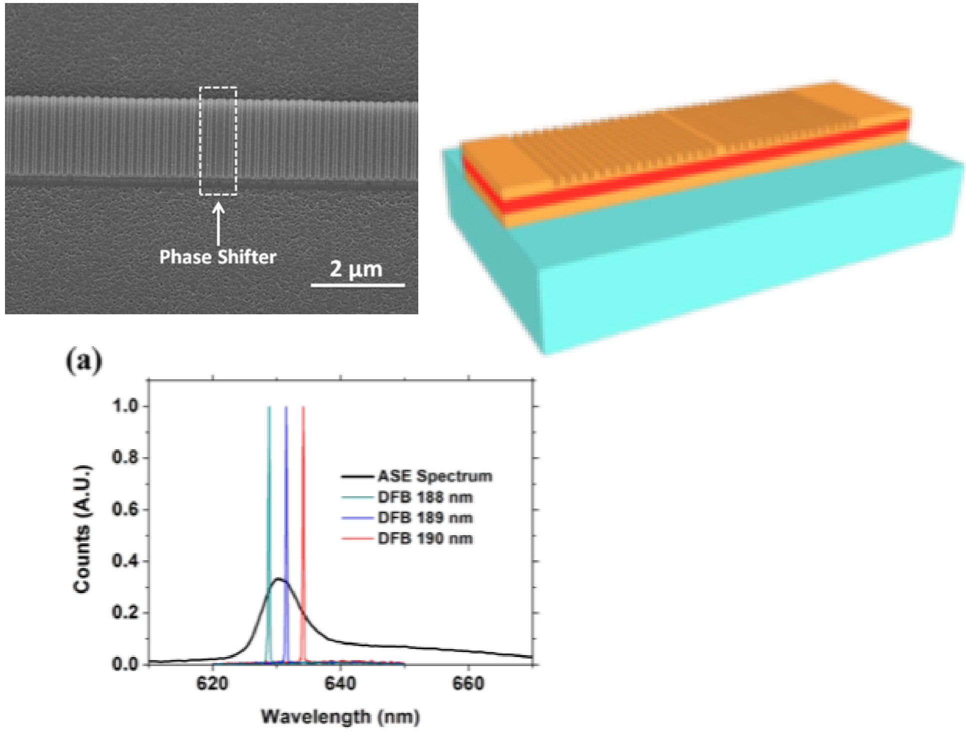
F. Peyskens e.a. , Nature Comm. 2019

COLLOIDAL QUANTUM DOTS

Alternative gain material (mostly in visible)

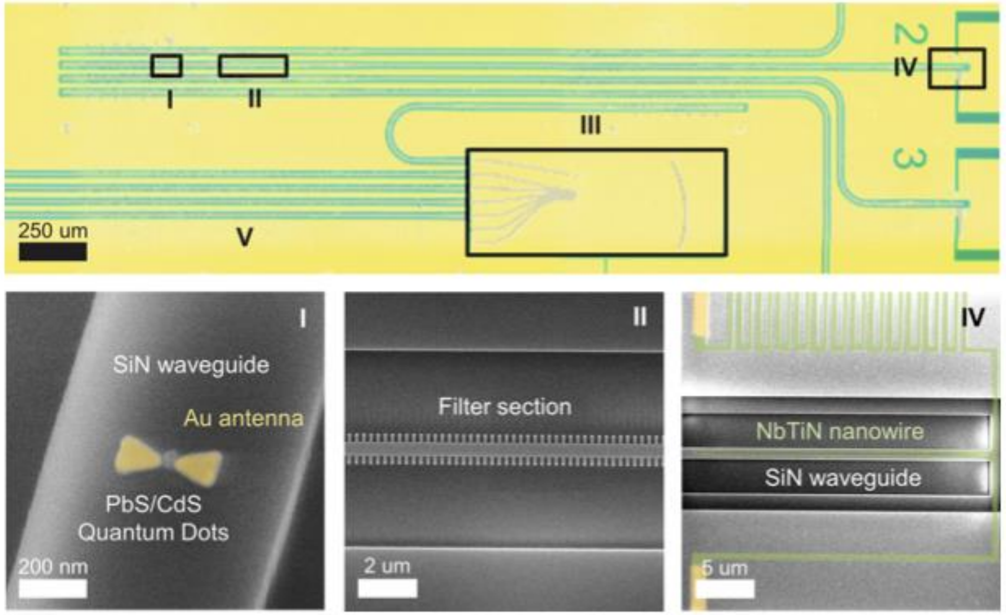
Also: explored single photon emission properties, integration with SNPD

DFB-laser from SiN/QD/SiN stack



Y. Zhu, ACS Photonics, 2017

PbS QD in plasmon antenna, PCG, SNPD



L. Elsinger, Nanoletters 2019

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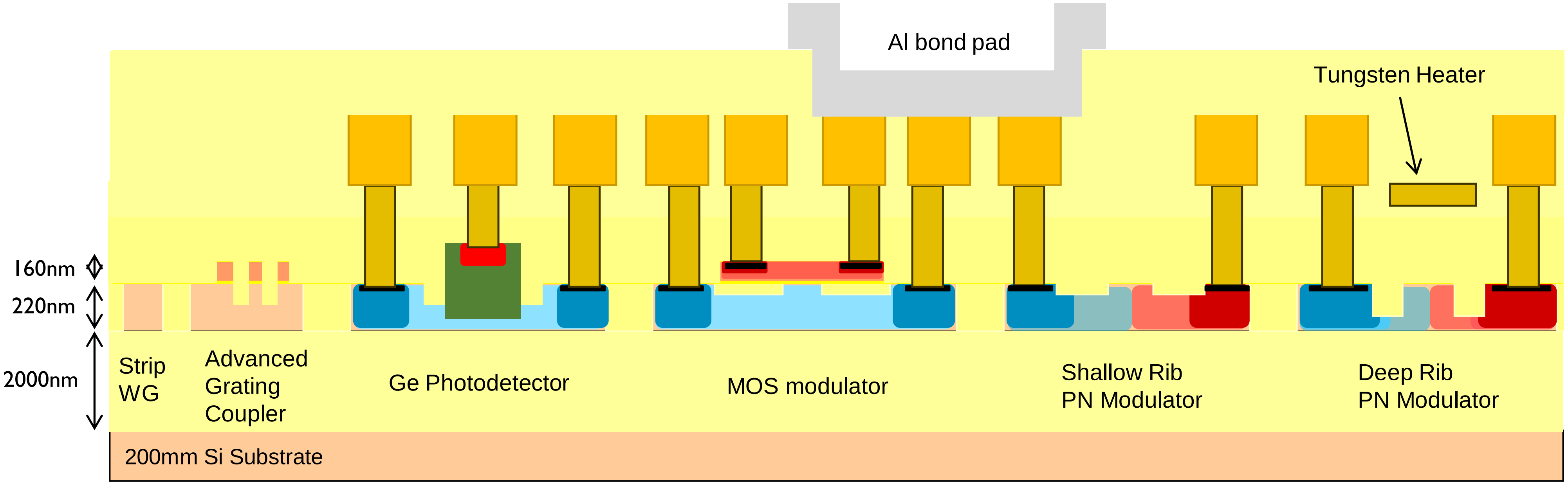
Collaboration Z. Hens, P. Geiregat (PCN, UGent)

III-V LASERS

LASERS FOR SILICON PHOTONICS

- How to integrate lasers in full silicon photonics platform ?
  - Problem: waveguides are covered with thick oxide/metal stack
  - Solution 1: Transfer-printing of III-V coupons in cavities



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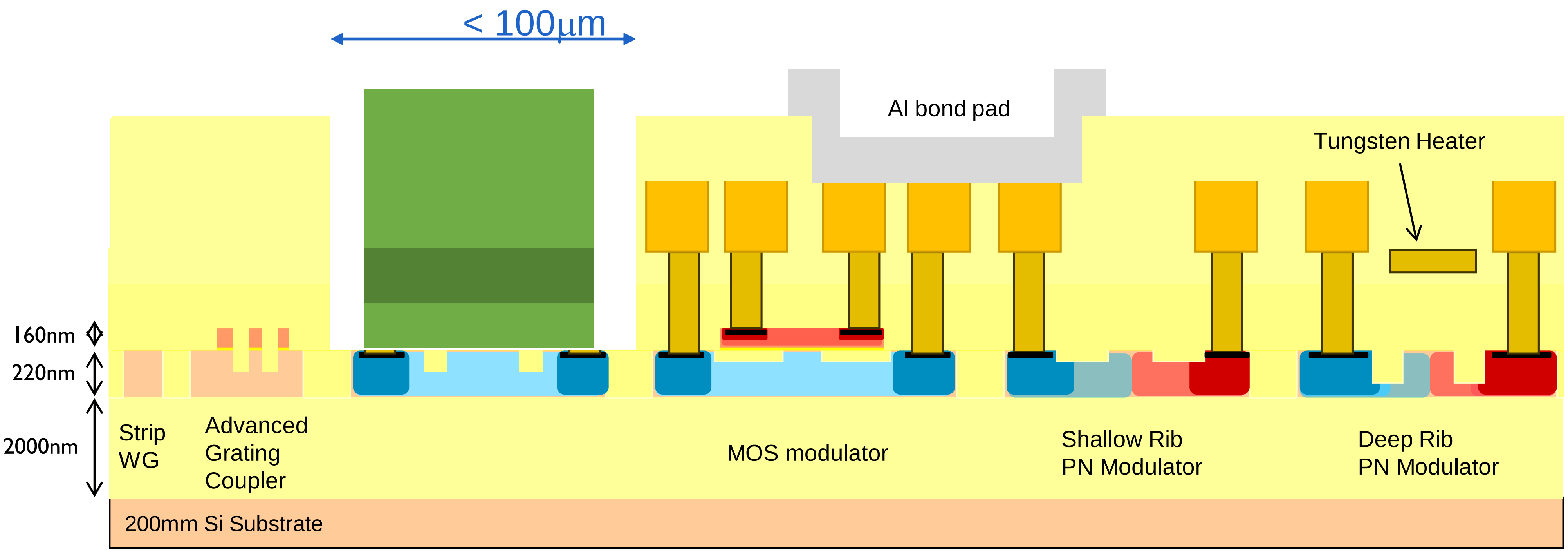

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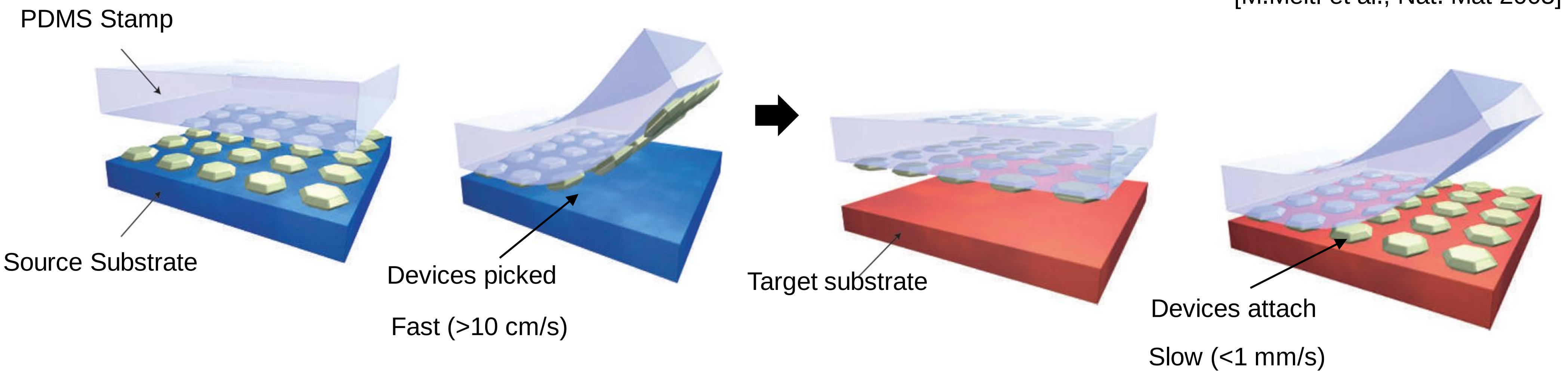
WHAT IS TRANSFER PRINTING ?

[M.Meitl et al., Nat. Mat 2005]



Approach:

- III-V dies partly processed on source wafer
- Transfer on target SPh-wafer using PDMS-stamp

Transfer printing promises:

- Collective postprocessing on target wafer
- Possibility for parallel transfer of multiple dies and area magnification
- No substrate removal needed (recycling of wafers, less waste)

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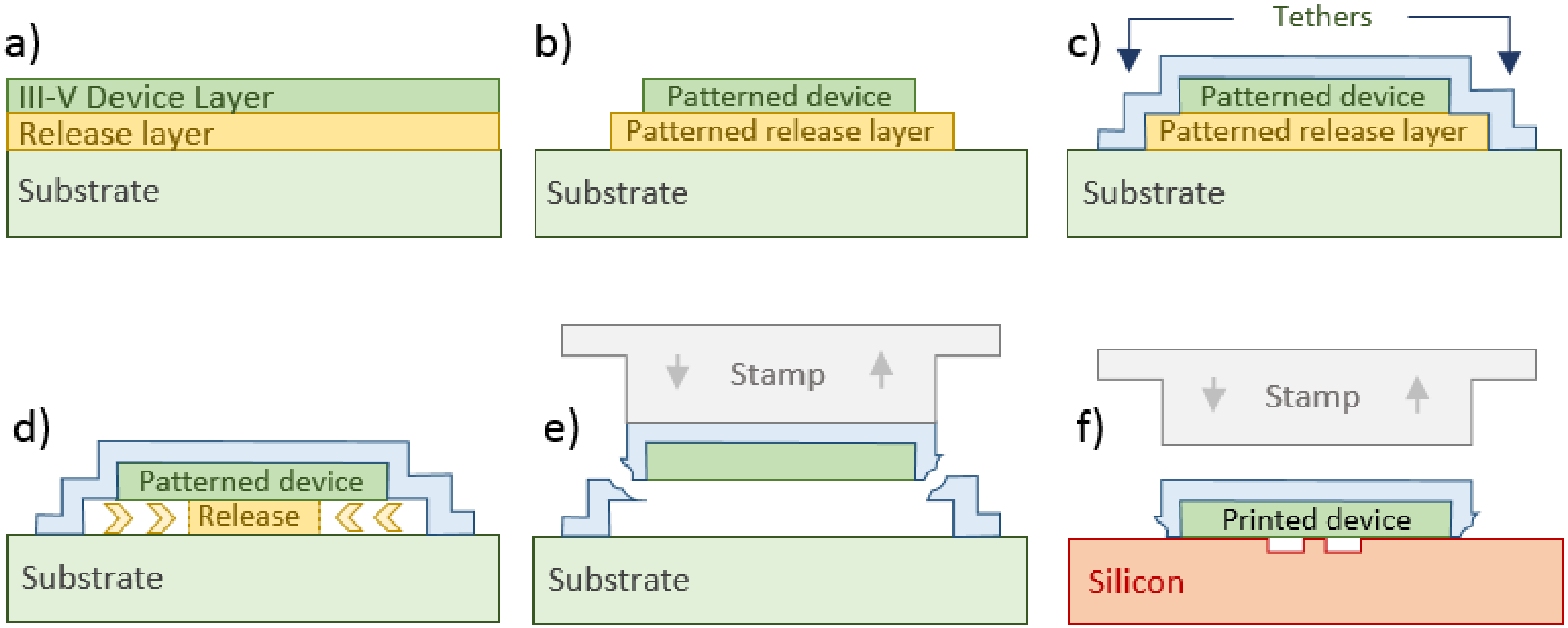
TRANSFER PRINTING

Enabling technology for heterogeneous integration on silicon photonics



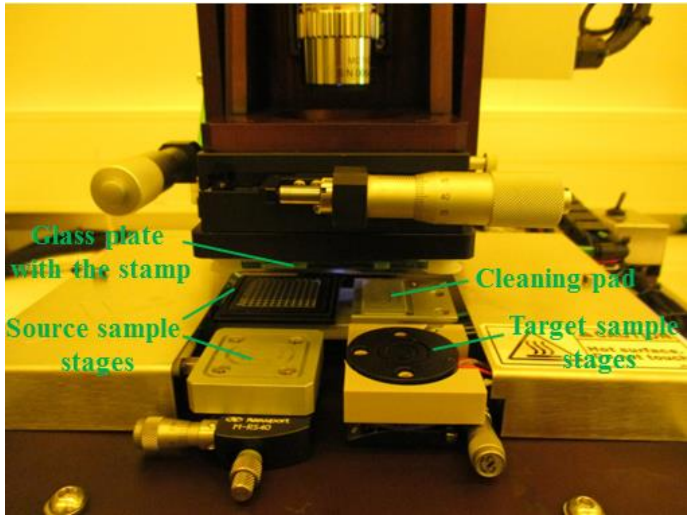
Transfer of <u>micro-scale </u>III-V coupons/devices to a Si target wafer

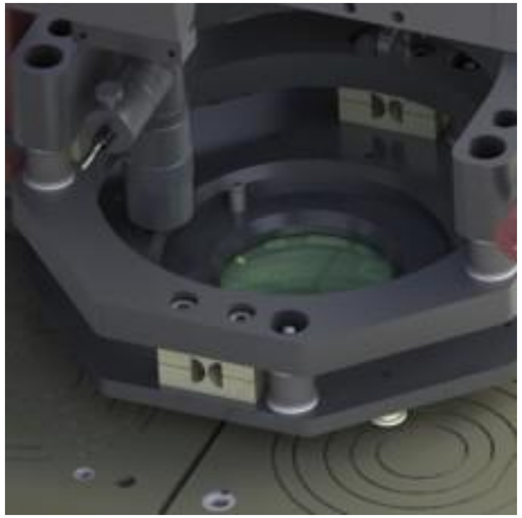
InP, GaAs, GaSb, SOI, thin films,2D materials, 0D materials

MICRO-TRANSFER-PRINTING (μTP)

PROCESS CARRIED OUT USING COMMERCIAL TOOL FROM X-CELEPRINT

Lab-scale tool at Photonics Research Group (Ghent)





Scalable to 300mm and panels

– Alignment accuracy promised by vendor: < 1 μm – 3 σ

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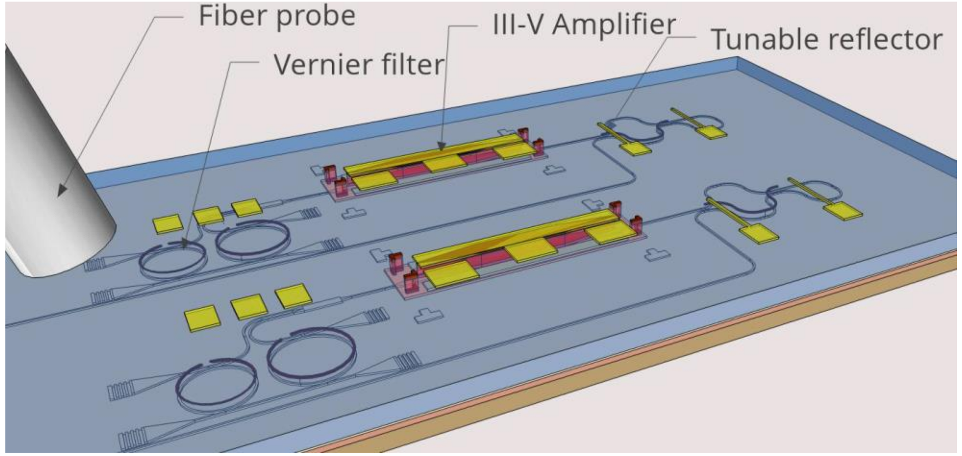
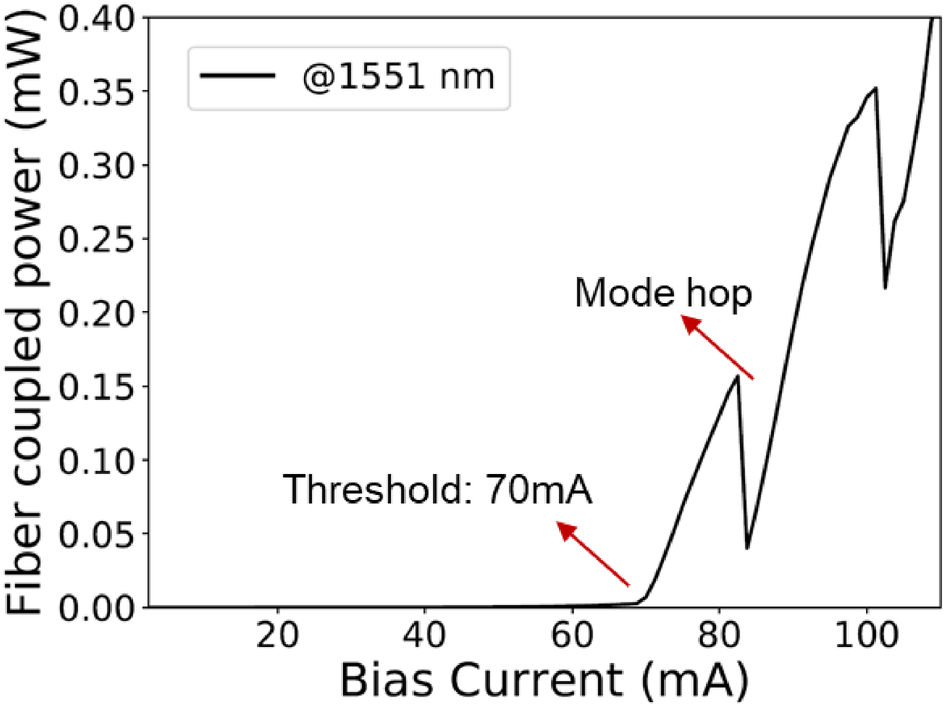
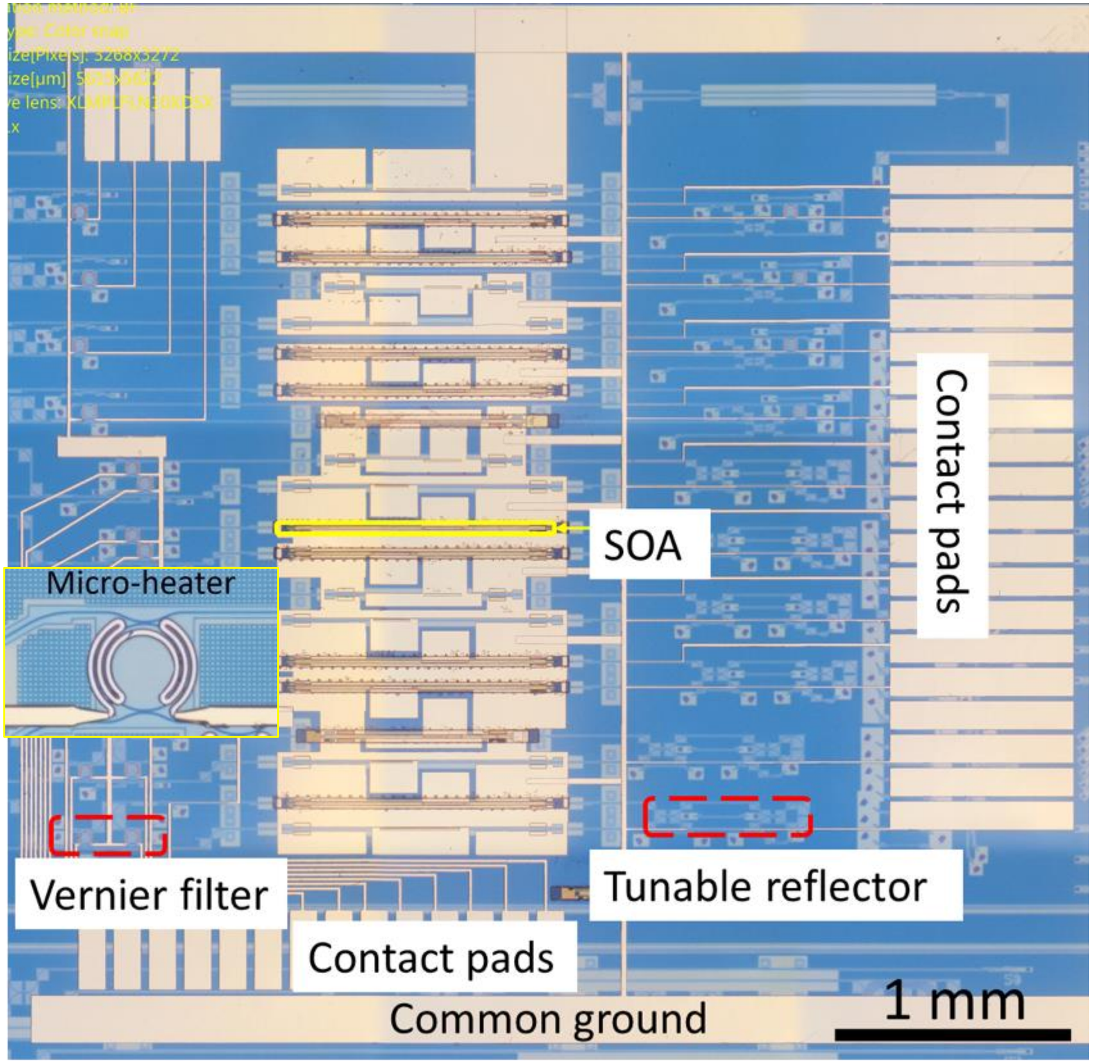
III-V-ON-SI WIDELY TUNABLE LASER WITH µTP

Prof. G. Roelkens & team





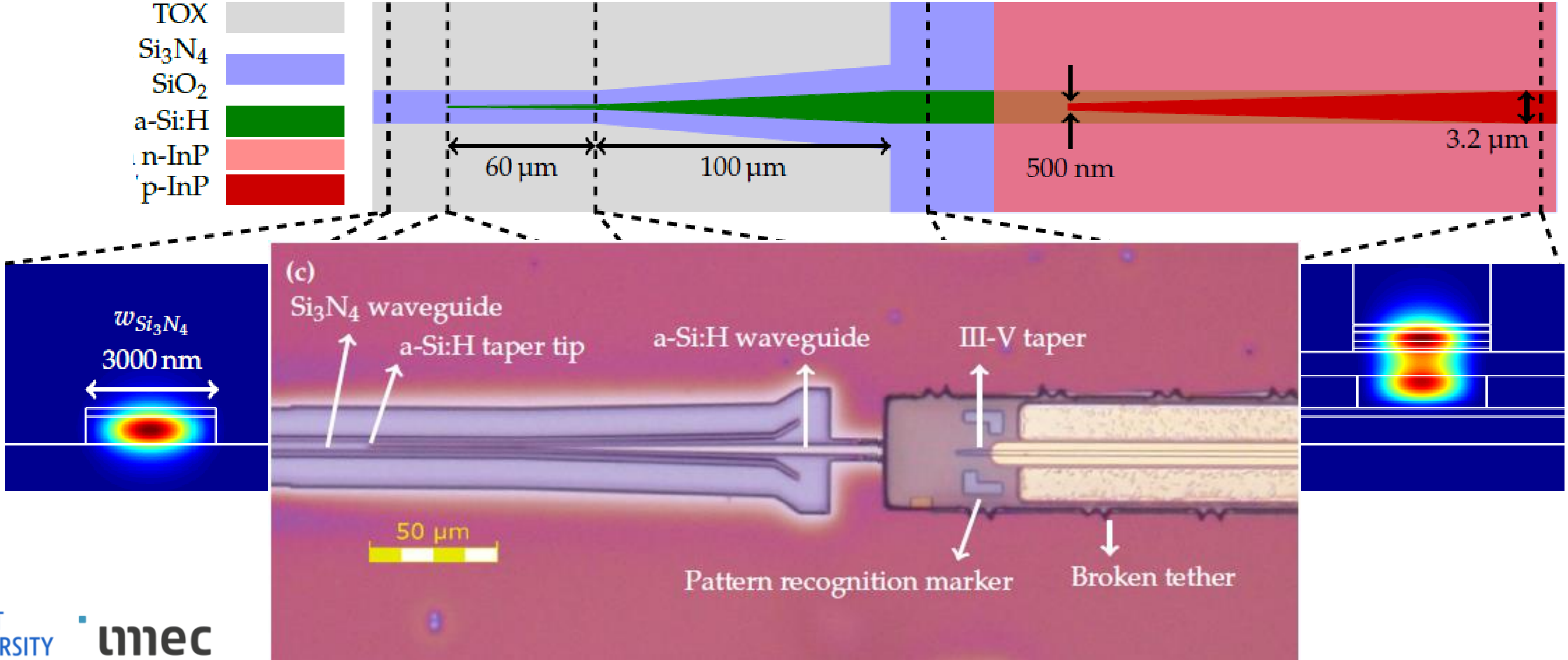


[J. Zhang et al., IEEE ECOC, 2019]

Integration of Amplifiers and Lasers on Silicon Nitride

Prof. B. Kuyken & team

- Why: low loss, broader wavelength range
- Non-trivial given large index mismatch between InP and SiN
- Solution: intermediate amorphous silicon layer layer



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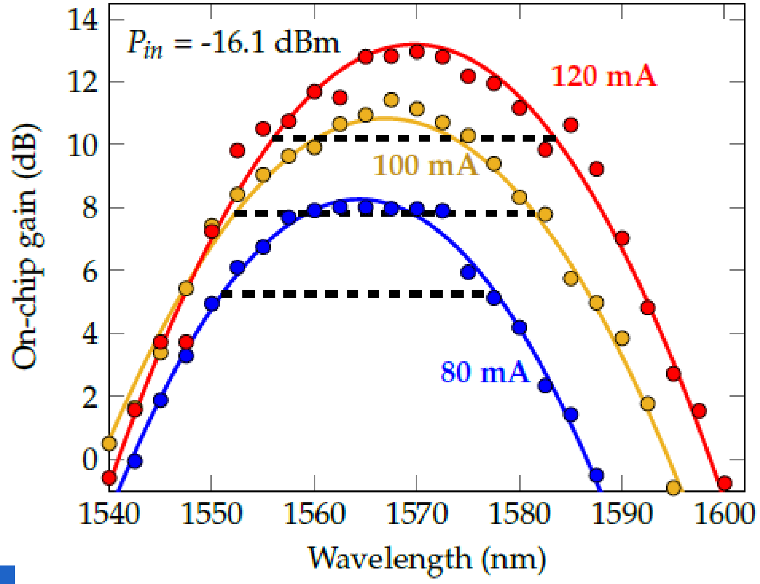
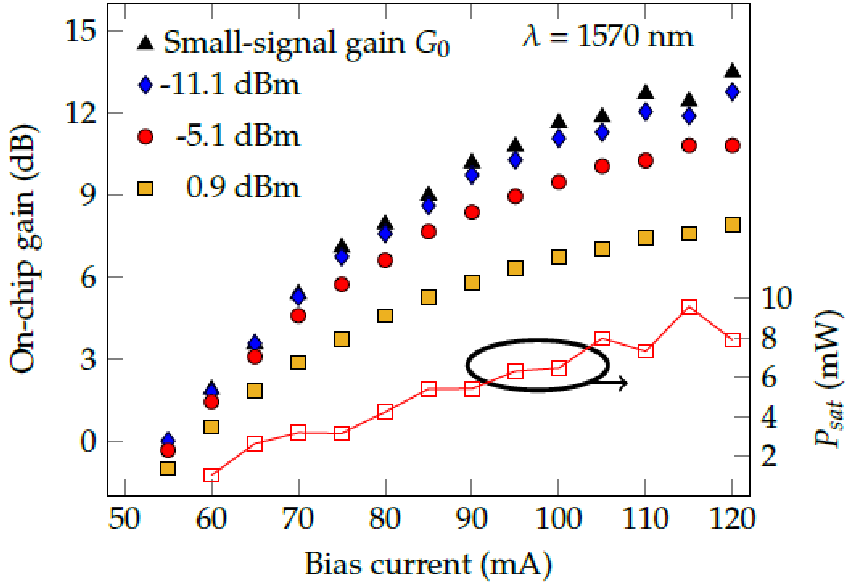
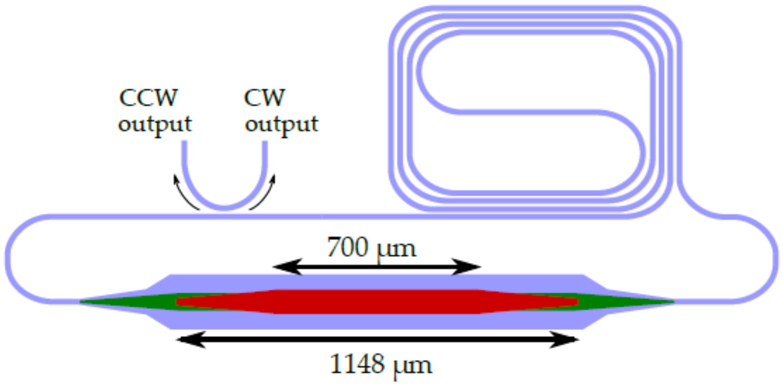
Integration of Amplifiers and Lasers on Silicon Nitride

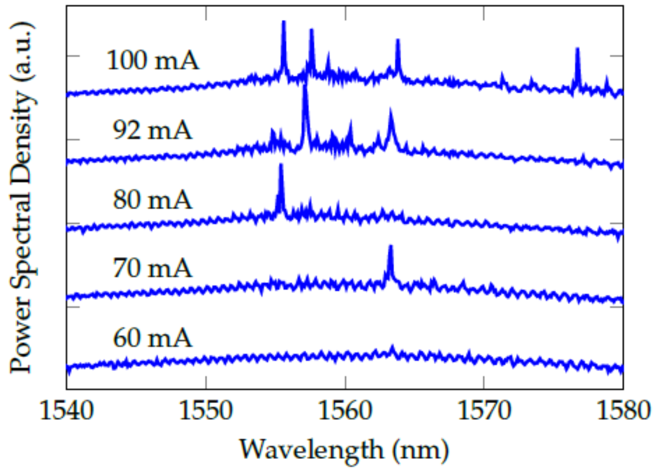
On-chip Gain

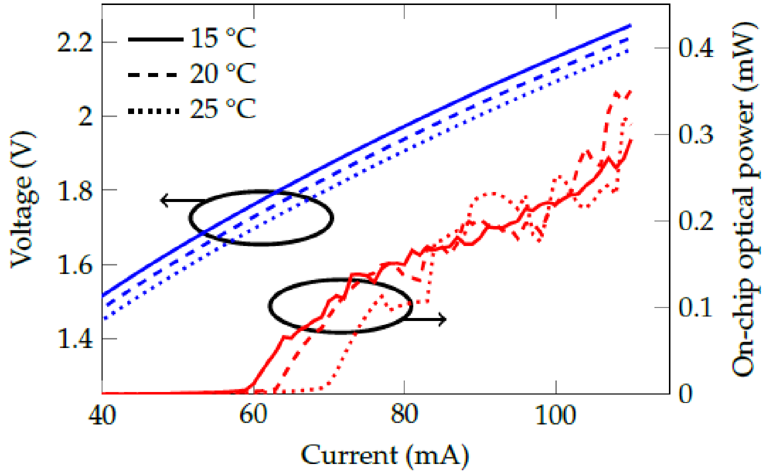




Ring-Laser







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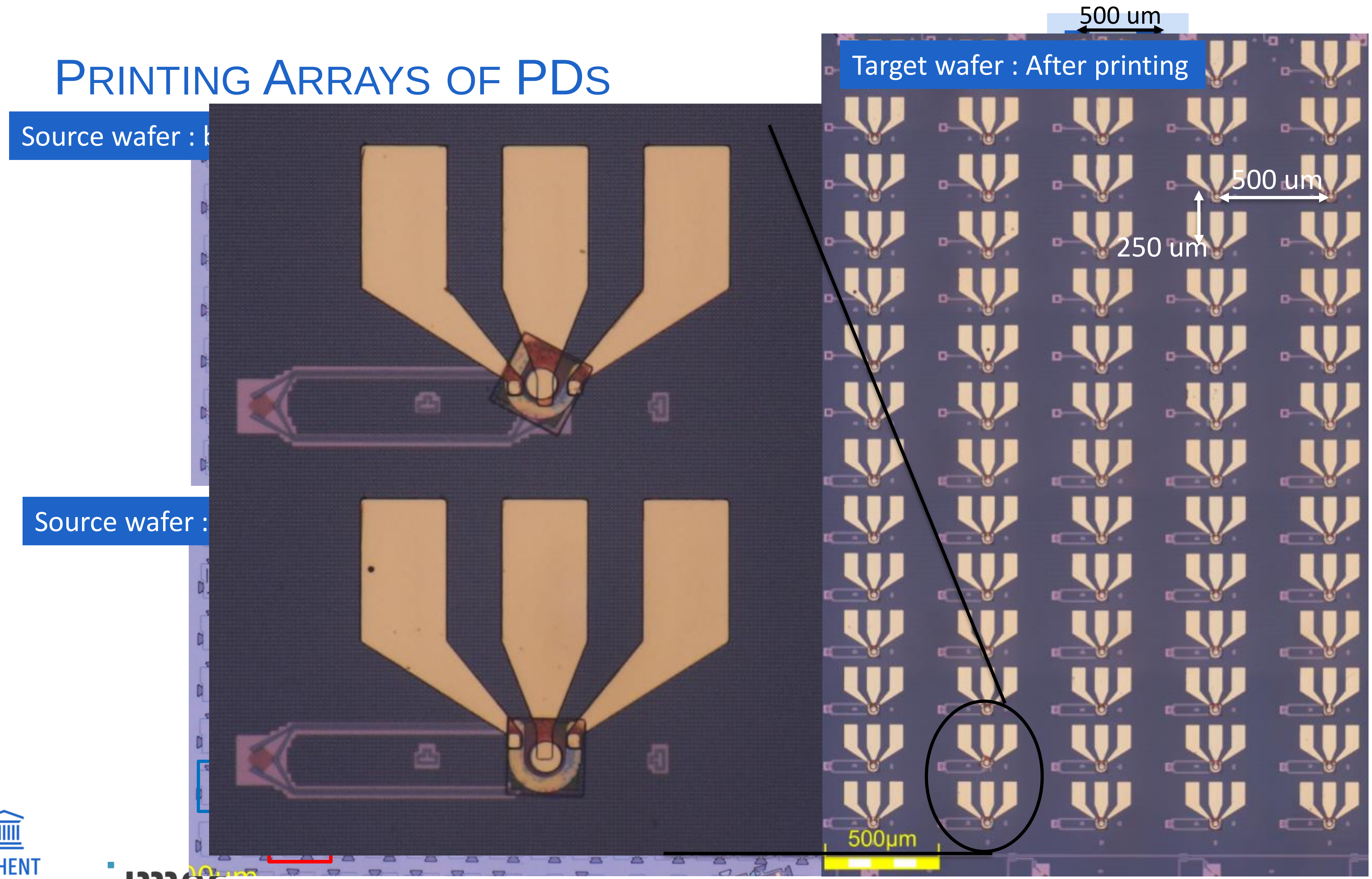
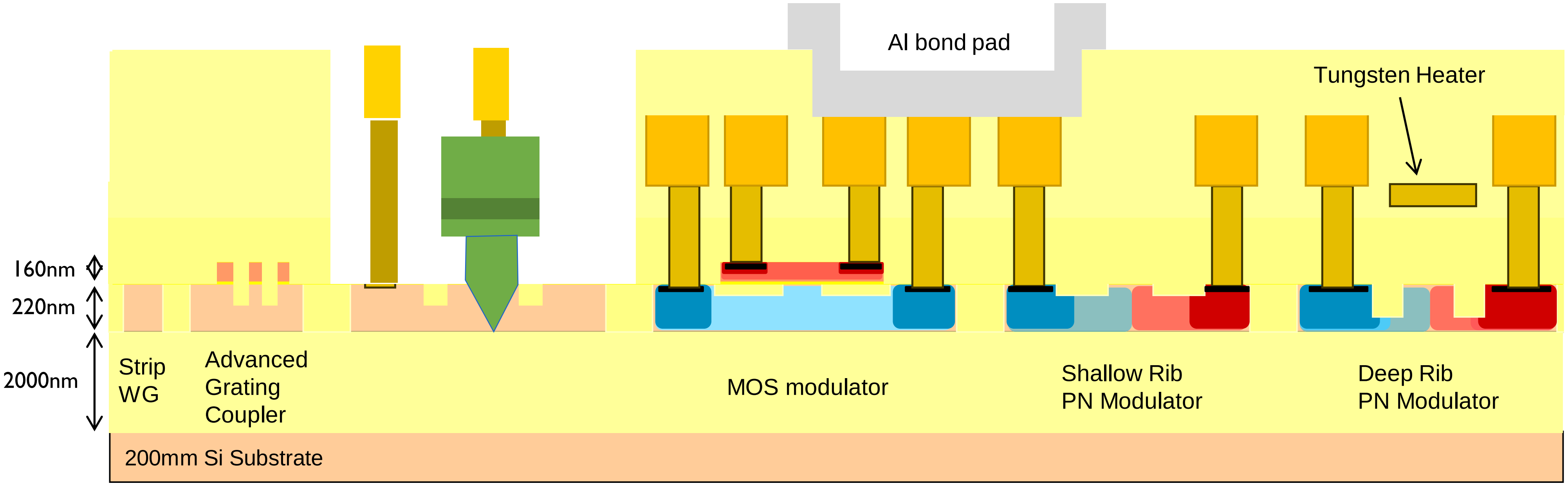
C. Op de Beeck, Optica 2020

PRINTING ARRAYS OF PDs



LASERS FOR SILICON PHOTONICS

- How to integrate lasers in full silicon photonics platform ?
  - Problem: waveguides are covered with thick oxide/metal stack
  - Solution 2: **Direct epitaxial growth** (III-V on silicon)



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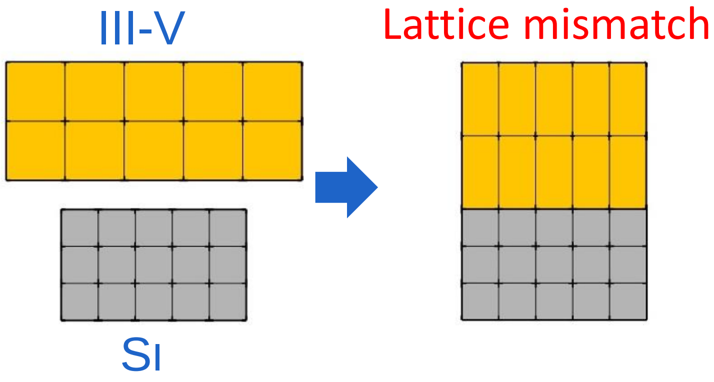
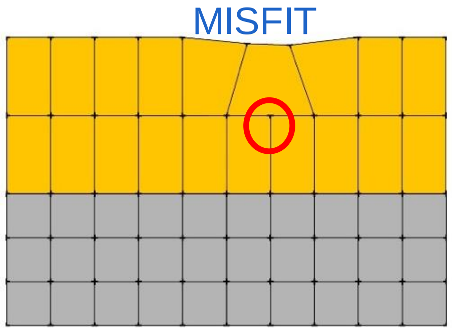
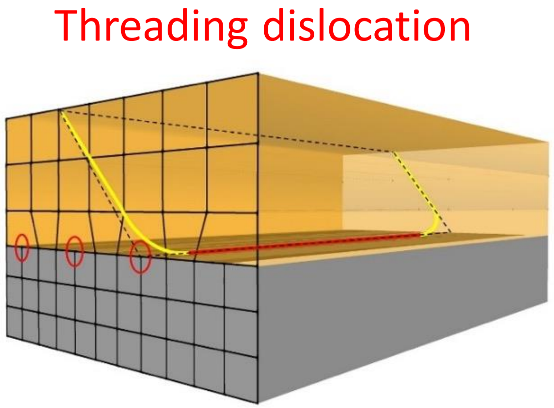
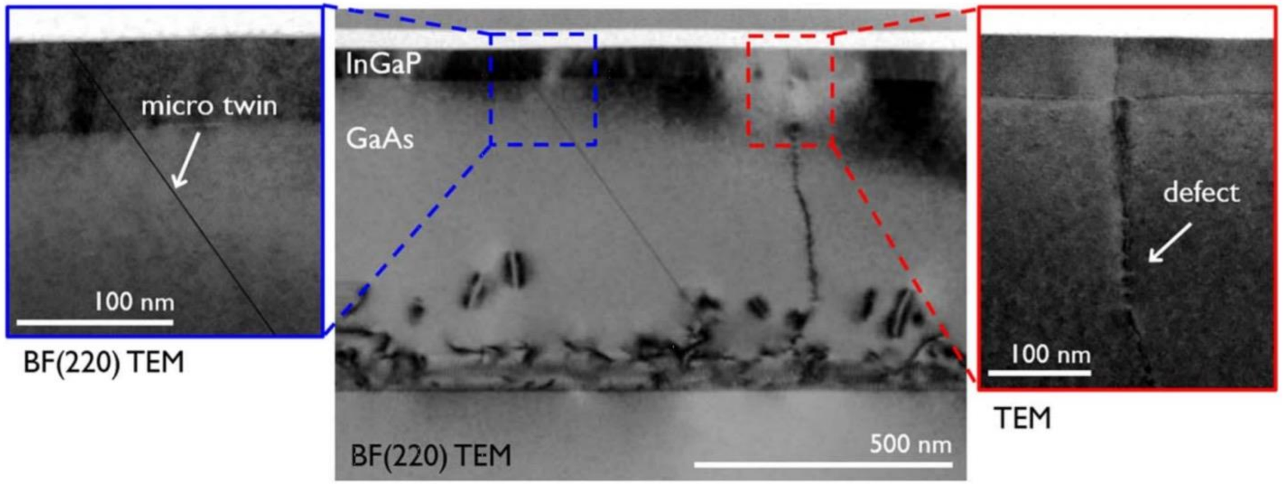
HETEROEPITAXY- CHALLENGES

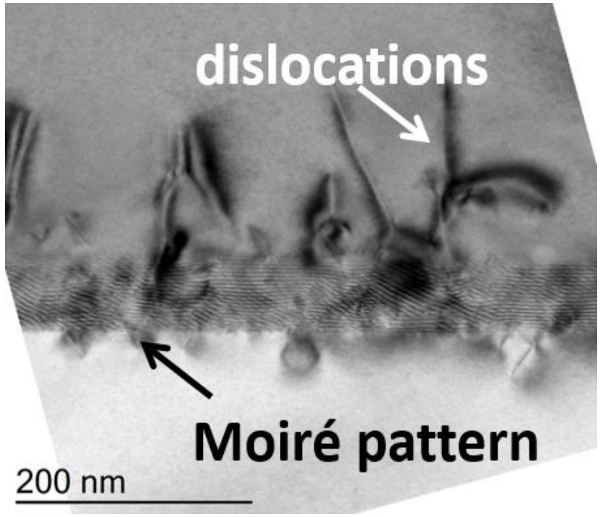






LATTICE MISMATCH RESULTS IN UNWANTED DEFECTS





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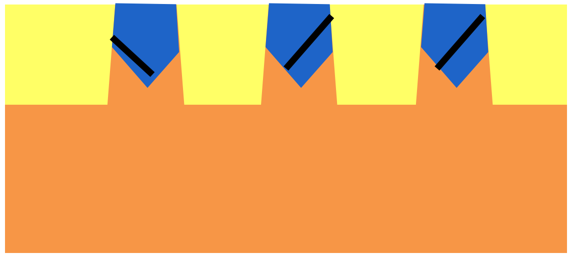
PROPOSED PROCESS: ASPECT RATIO TRAPPING

a) Etching ridges in silicon

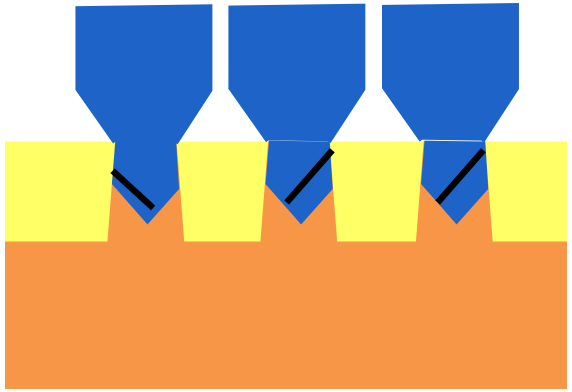
b) Planarization

c) KOH-etch silicon

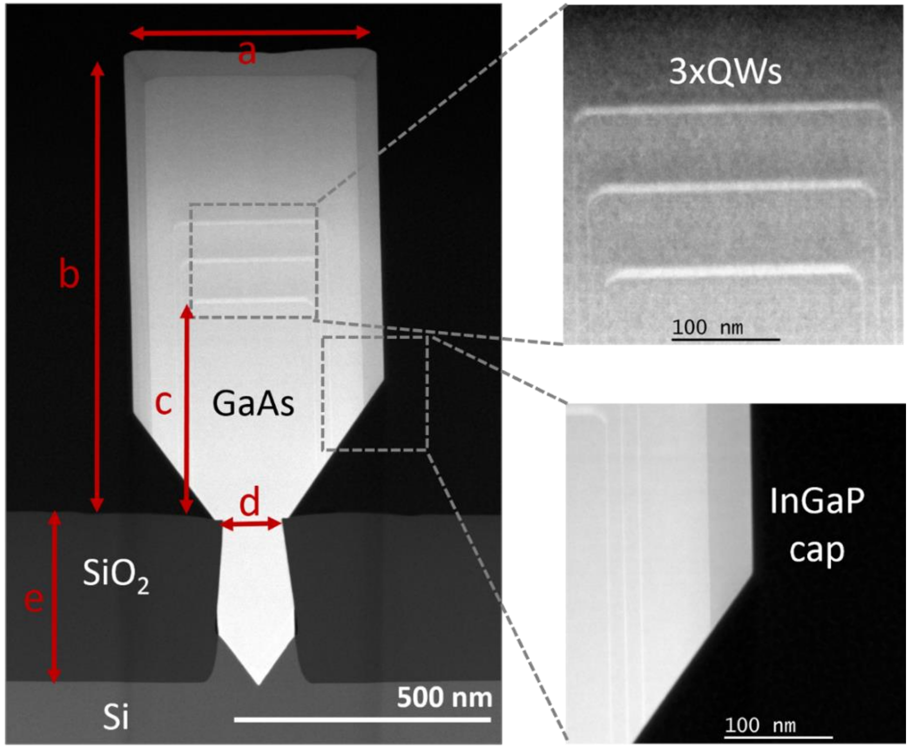
d) Nucleation and growth in trenches



e) Further growth out of trenches



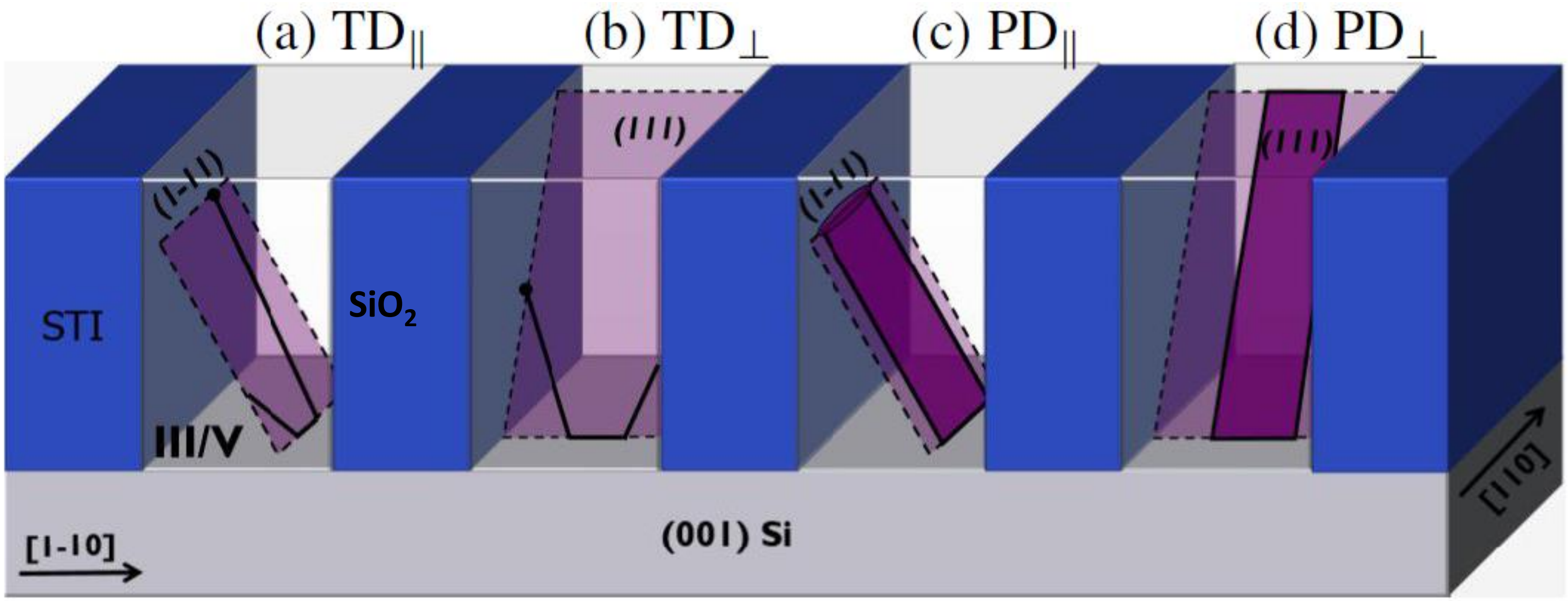
Reference sample



Developed by B. Kunert e.a., imec

ASPECT RATIO TRAPPING (ART)

- High-AR SiO_2 trenches enable **trapping of threading dislocations**



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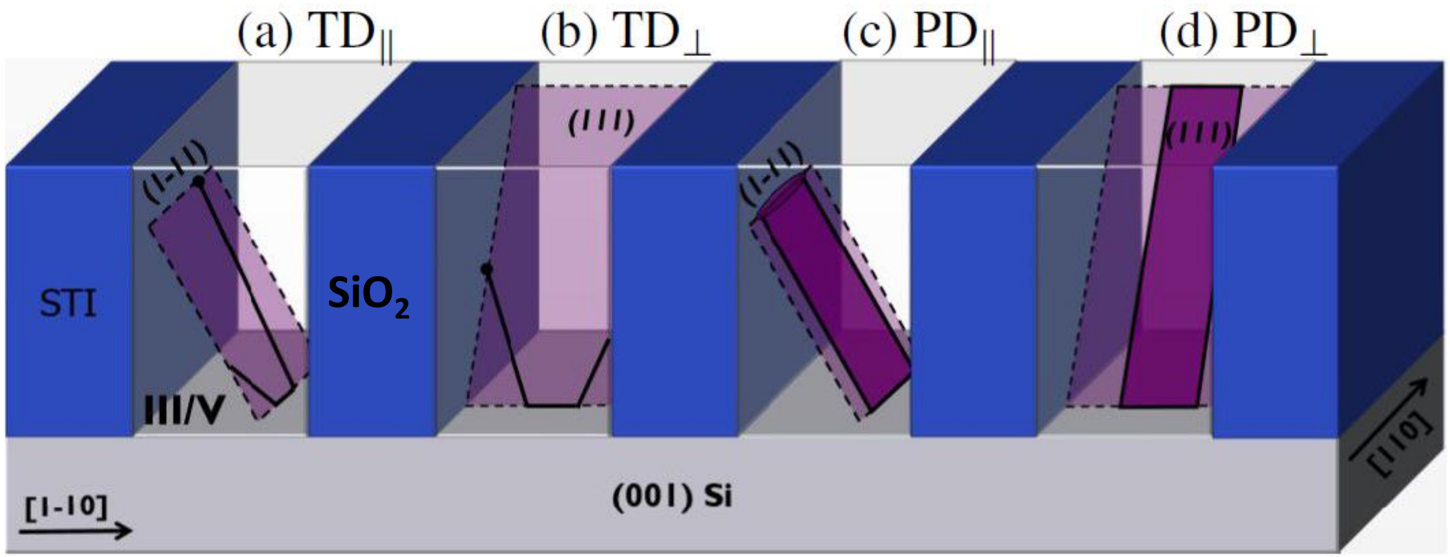
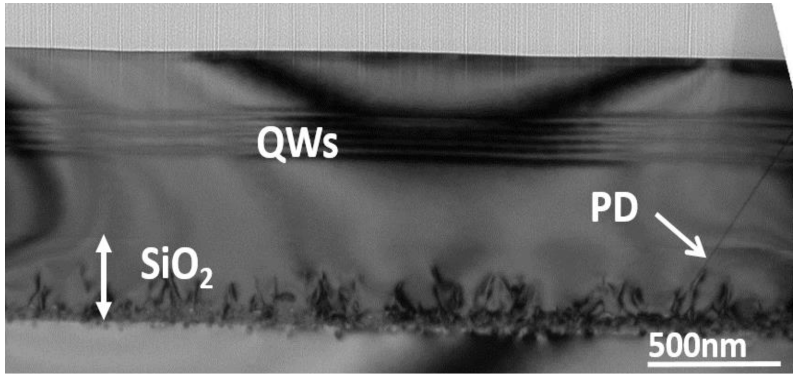
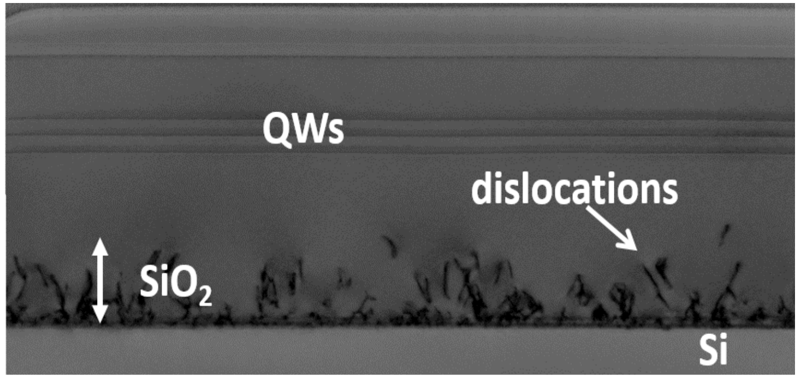


Longitudinal TEM-pictures



100nm trench



200nm trench

TD < $3x10^6 cm^{-2}$
(limited by measurement)
PD < 0.14–0.45µm-1

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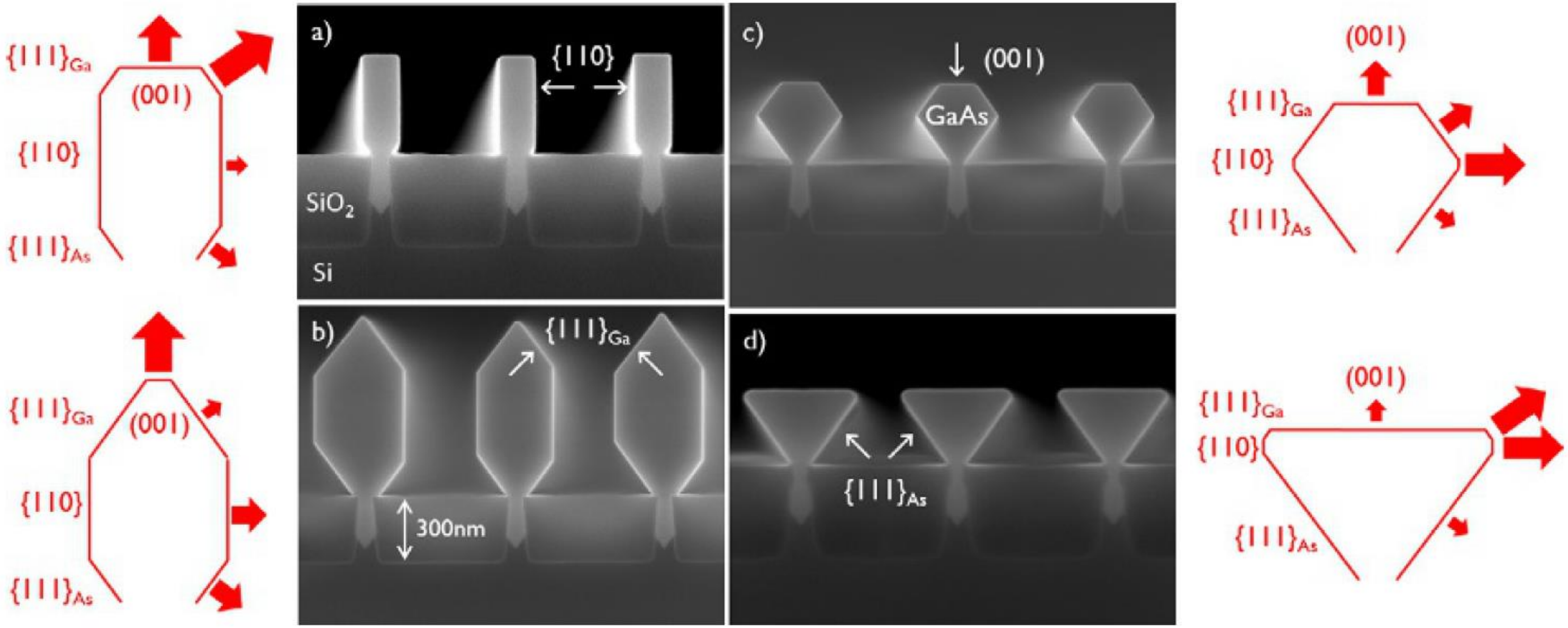
NANO-RIDGE ENGINEERING (NRE)

Control growth rate on different crystal planes to obtain well-defined nano-ridge profile
Higher growth rate facets disappear, whereas facets with **lower growth rates define the nano-ridge profile**



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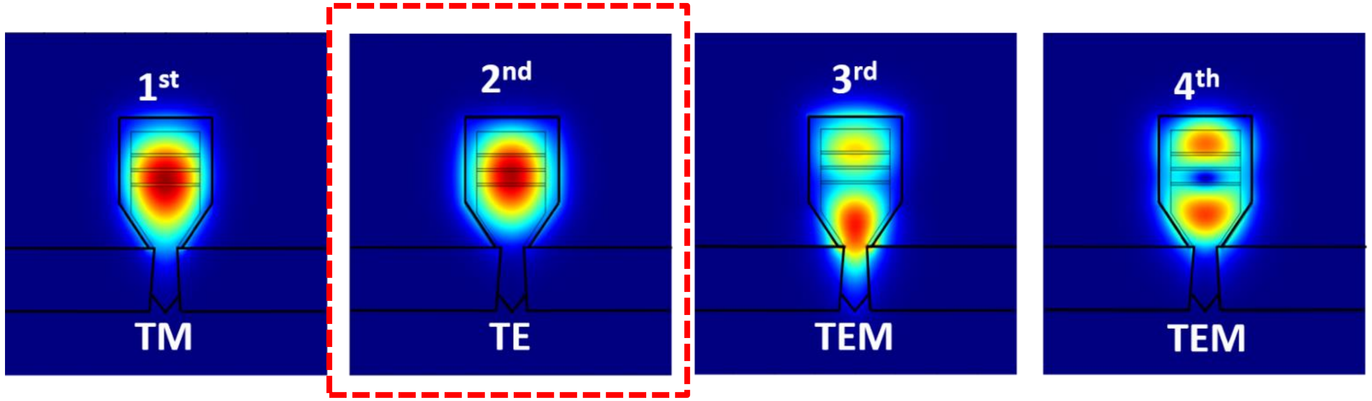
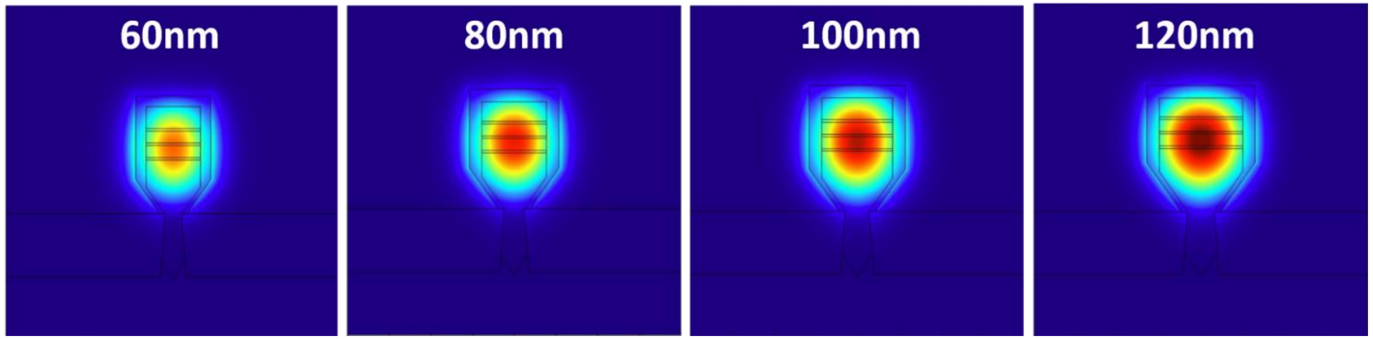
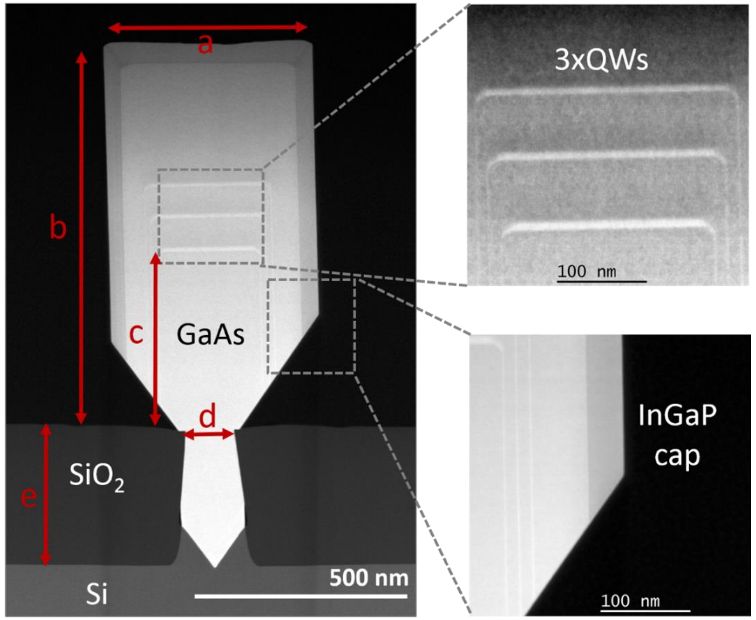
1μM-WAVELENGTH NANO-RIDGE LASER

TRANSVERSAL OPTICAL MODES IN NANO-RIDGE WITH 100NM-TRENCH WIDTH



TE-LIKE GROUND MODES IN NANO-RIDGES





$\mathbf{d}(nm)$	n_{eff}
60	3.022
80	3.122
100	3.167
120	3.210

Y. Shi, OPTICA, 4(12), p.1468-1473 (2017)

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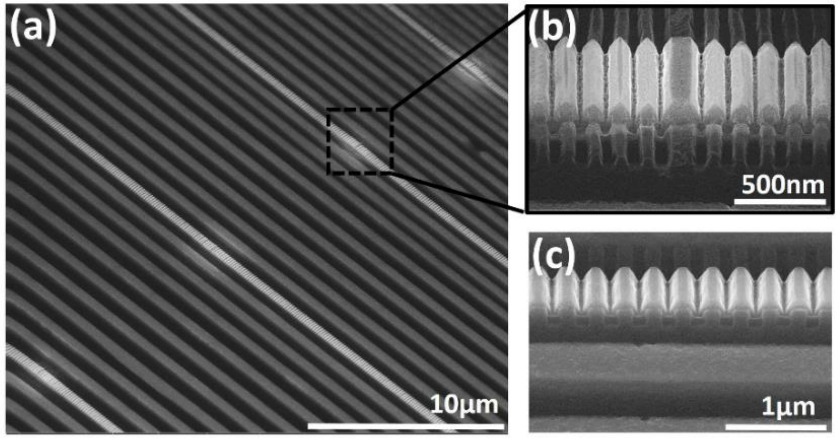
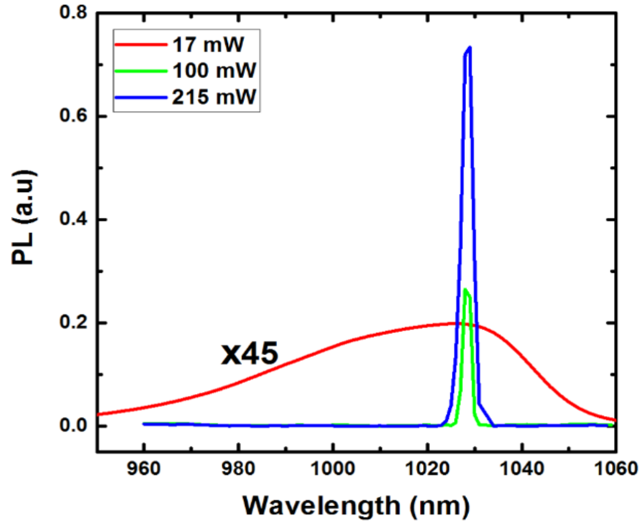
λ/4-SHIFT INDEX COUPLED DFB LASER

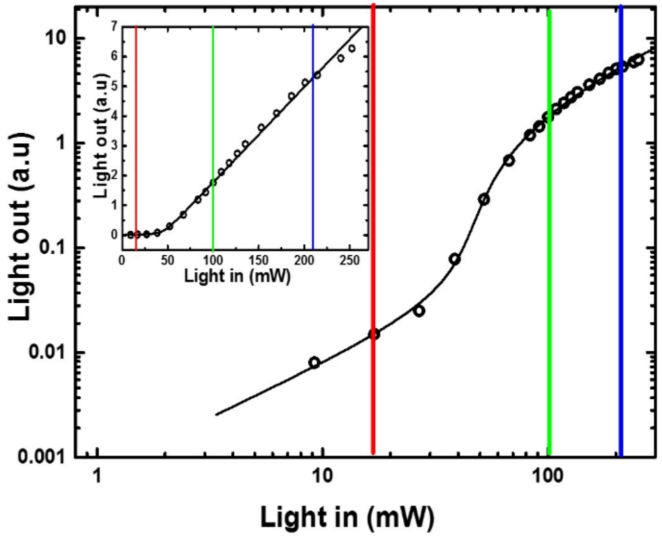
Etched Grating



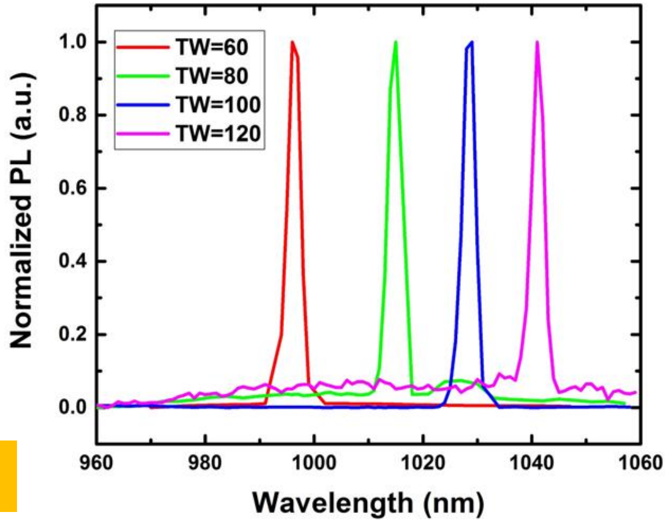
MEASURED SPECTRUM



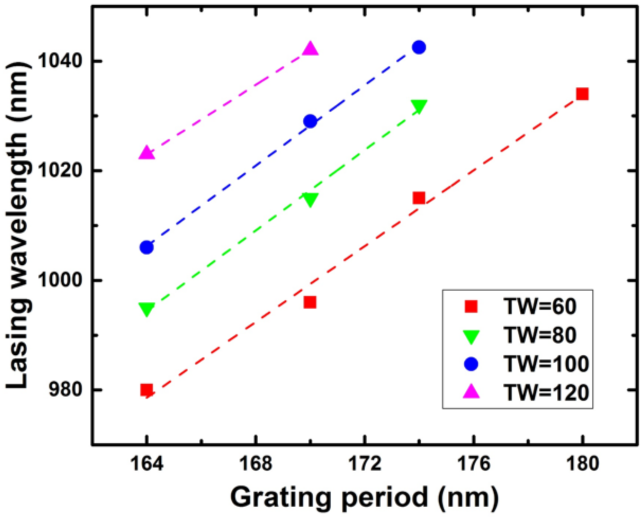
LIGHT-IN LIGHT OUT



SPECTRA FOR NANO-RIDGES WITH DIFFERENT TRENCH



WAVELENGTH TUNING



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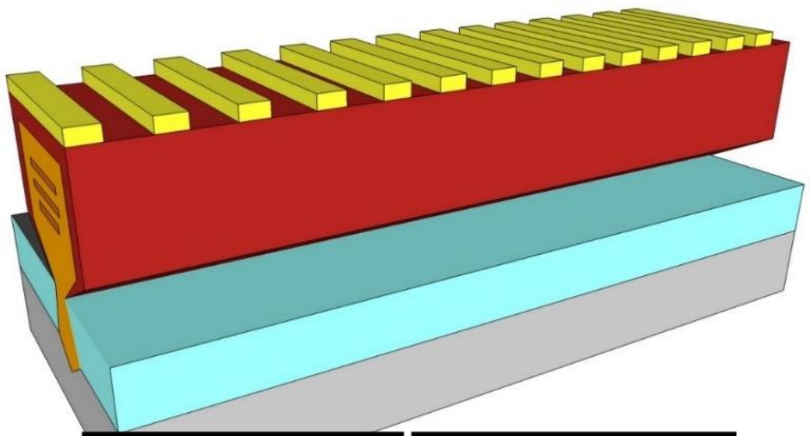
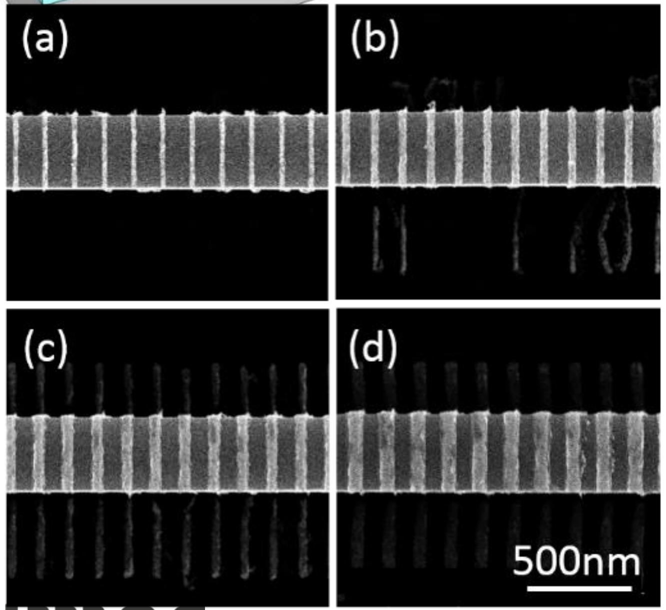
Y. Shi, Optica, 4(12), p.1468-1473 (2017)

DFB-LASER WITH METAL GRATING

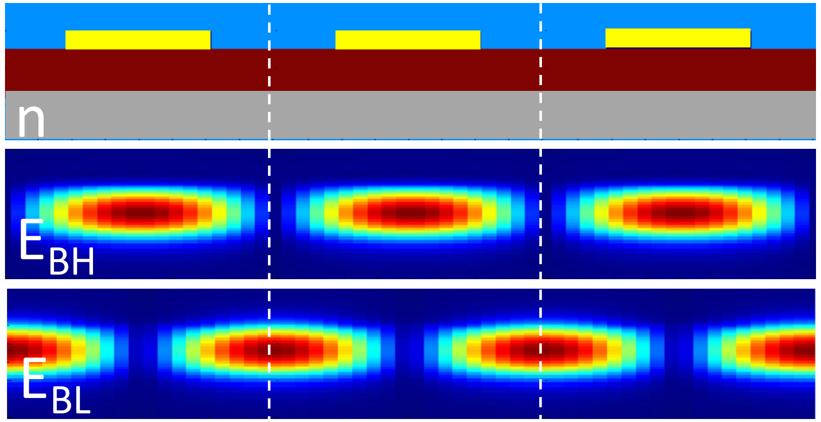
METAL GRATING ON NANO-RIDGE





Continuous Au-contact: $\alpha_{TE} = 74\ cm^{-1}$

Grating with 40% duty cycle: $\alpha_{E_{BL}} = 7 cm^{-1}$

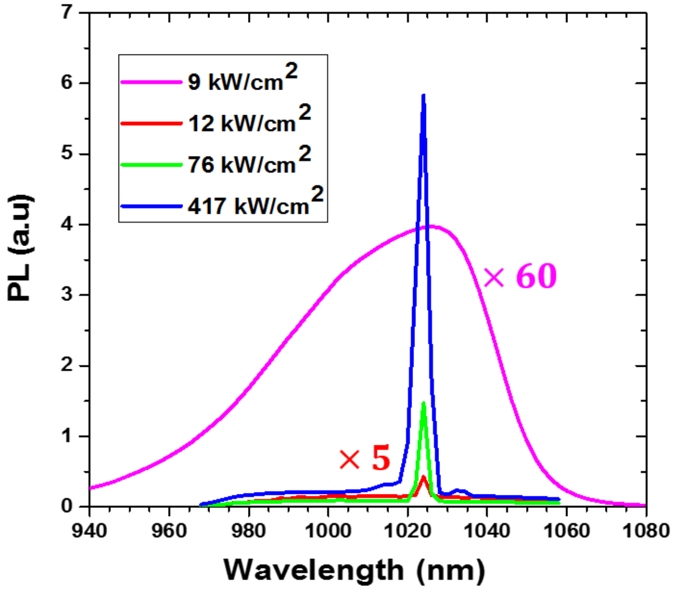


Bloch modes: E_{BH} (high overlap)
E_{LH} (low overlap)

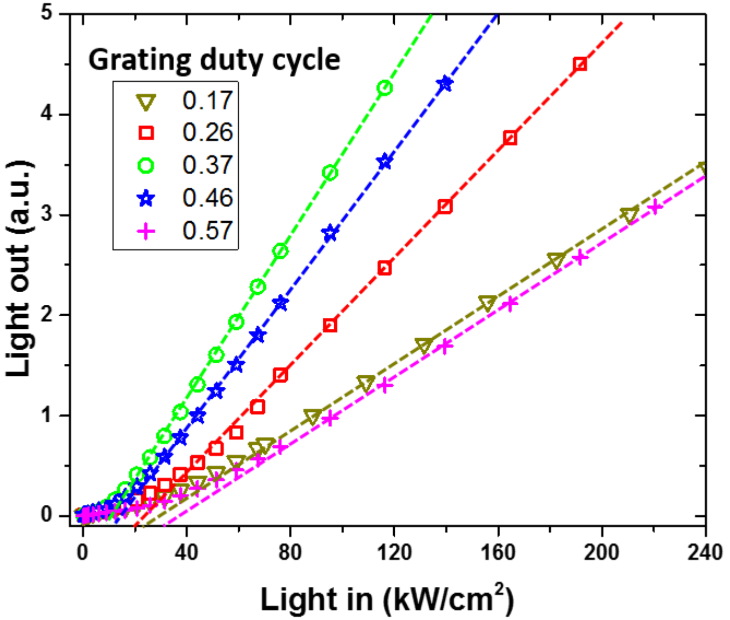
Loss: $\alpha_{E_{BH}} \approx 10 \times \alpha_{E_{BL}}$

DFB-LASER WITH METAL GRATING

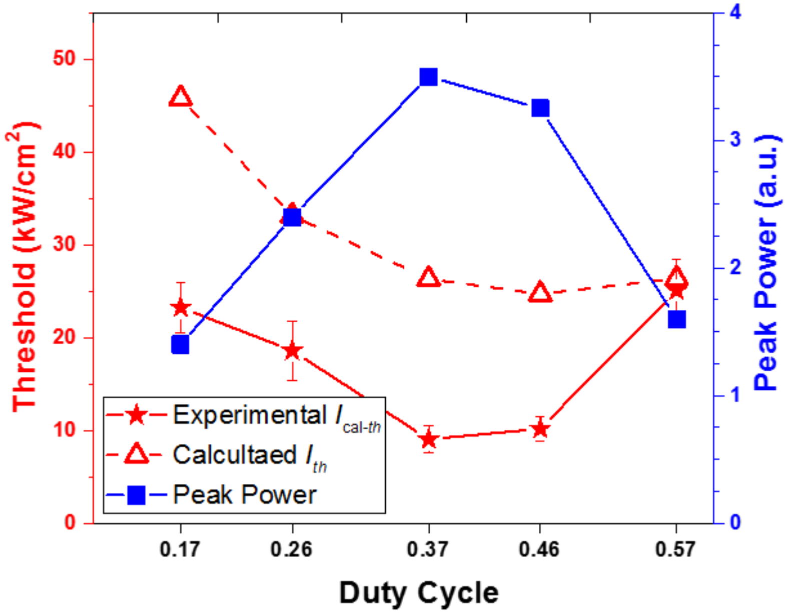
Measured spectrum



Light-in Light out



Threshold/Power vs Duty Cycle



Trade-off between coupling factor and loss results in optimal duty cycle of 40%

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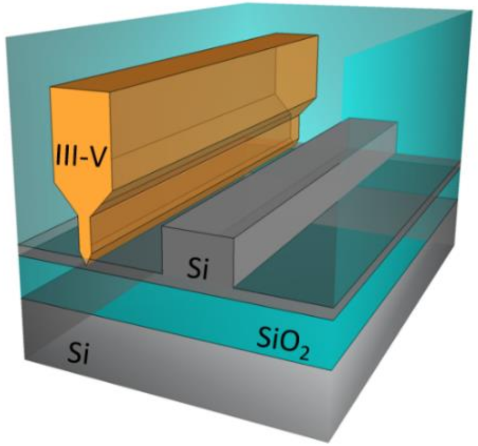
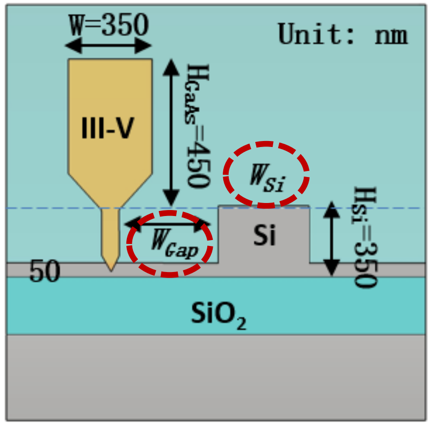
Coupling light to silicon waveguide

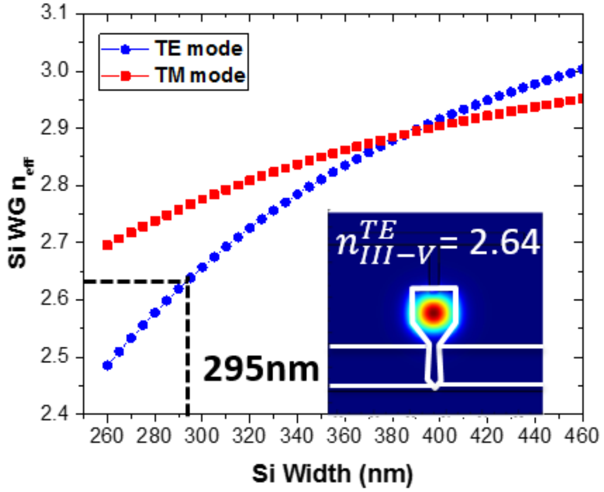
Proposed configuration



Cross section



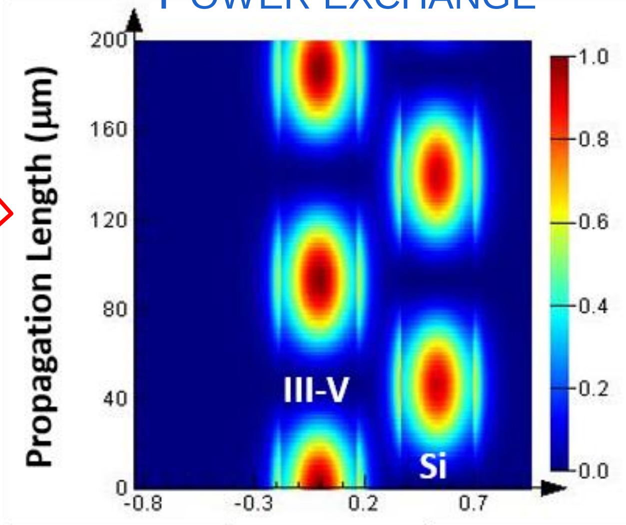
Phase match condition



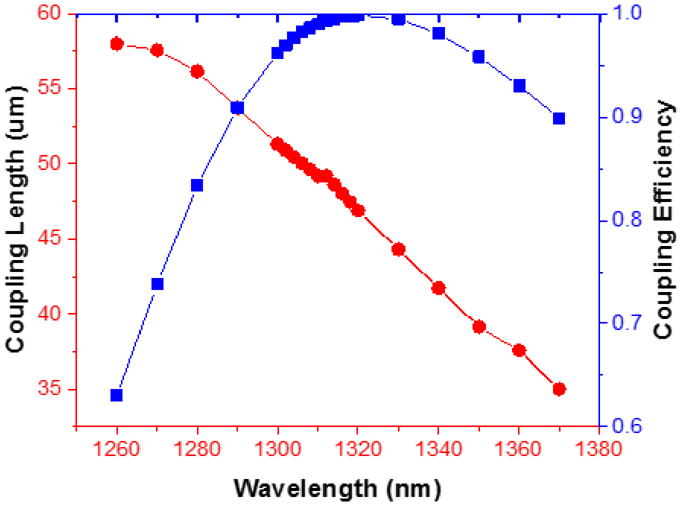
100% coupling

Sensitive to variation

Power exchange



Coupling in O-band



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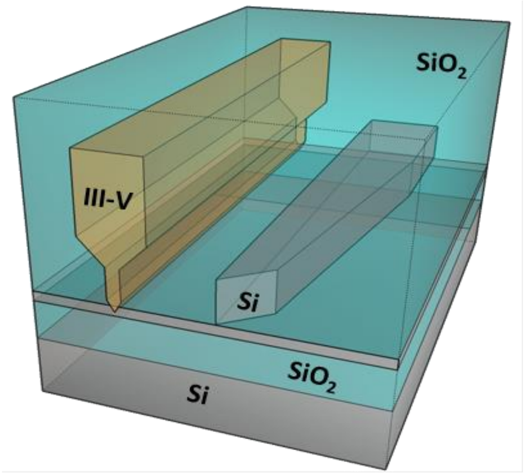
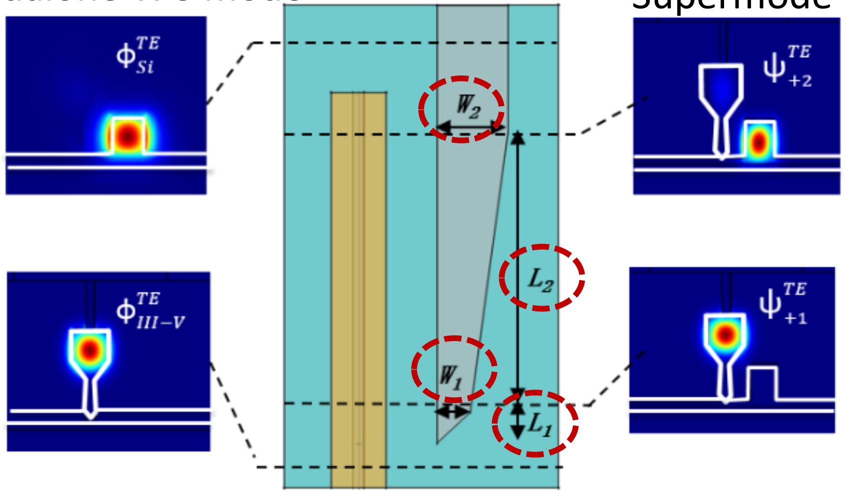
IMPROVED VERSION

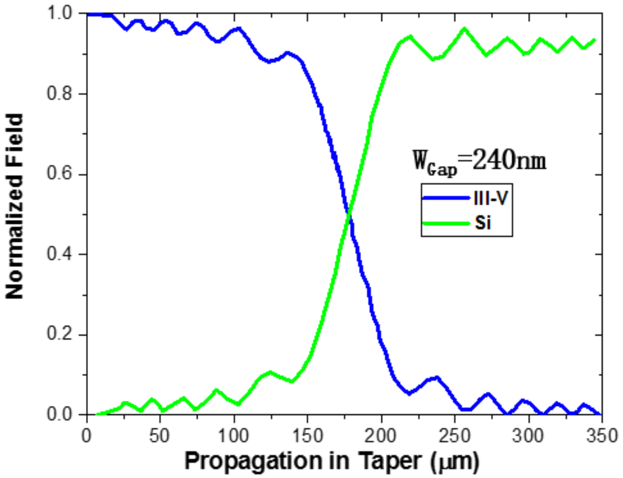
PROPOSED CONFIGURATION



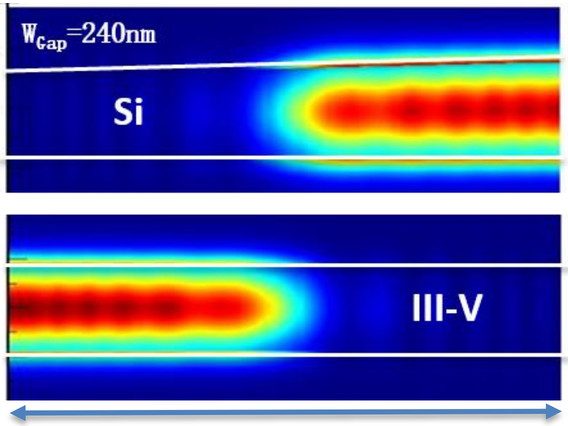
TOP VIEW



POWER EXCHANGE



POWER EXCHANGE



L=310μm

98% coupling
Long footprint

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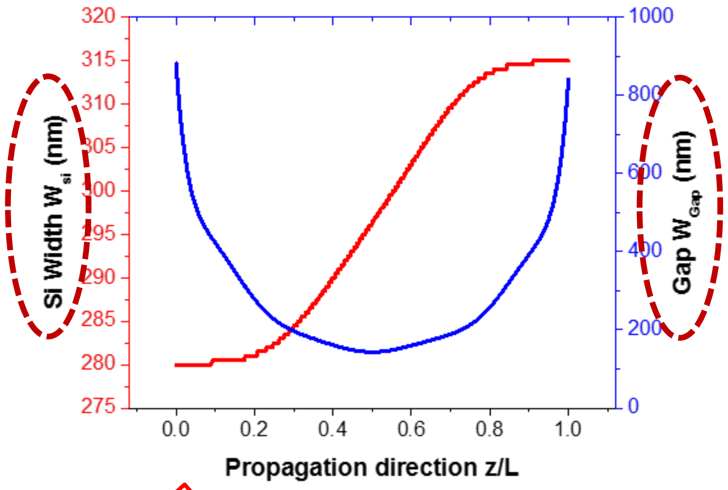
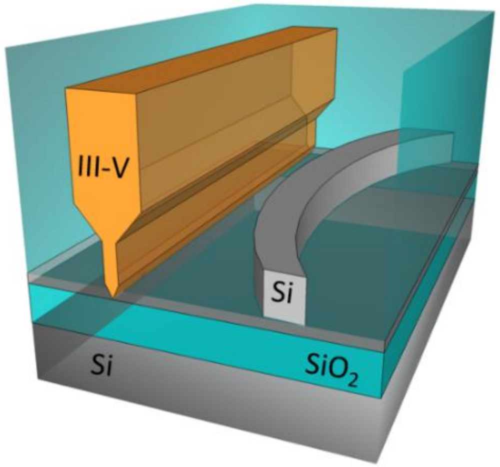
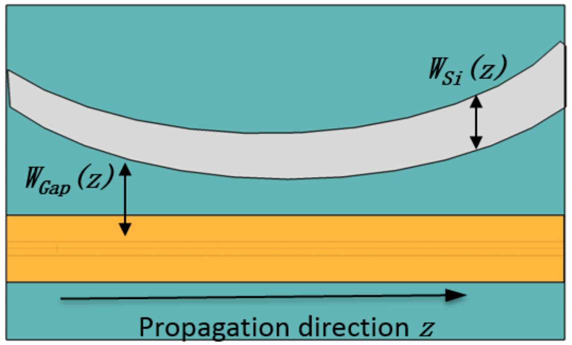
Further improved version



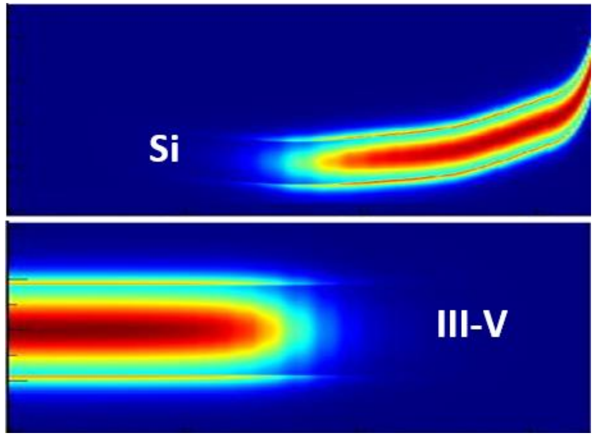
Proposed configuration



Top view



Power exchange



99% coupling
Compact size
High tolerance

Blackman function

$$\kappa(z) = \kappa_{max} \cdot sin\theta(z)$$

$$\Delta\beta(z) = -\Delta\beta_{max} \cdot cos\theta(z)$$

$$\theta(z) = \frac{\pi z}{L} - 0.25sin\frac{2\pi z}{L} - 0.07sin\frac{4\pi z}{L}$$

Hsien-kai Hsiao, et al. Midinfrared broadband achromatic astronomical beam combiner for nulling interferometry. Applied optics, 49(35):6675–6688, 2010.

Y. Shi, Optics Express 27(26), p.37781-37794 (2019)

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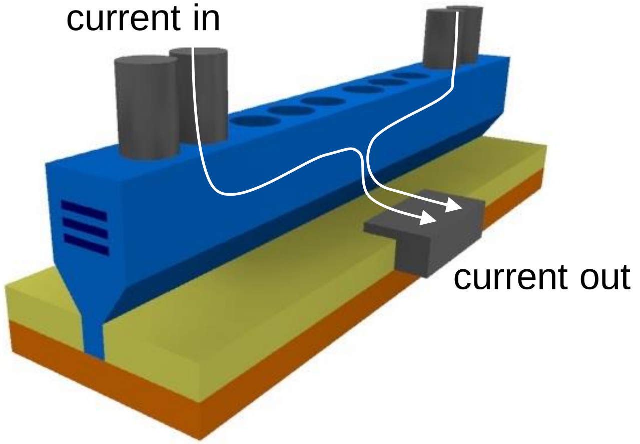
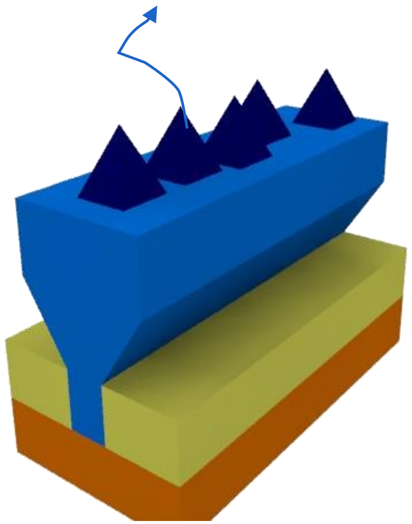
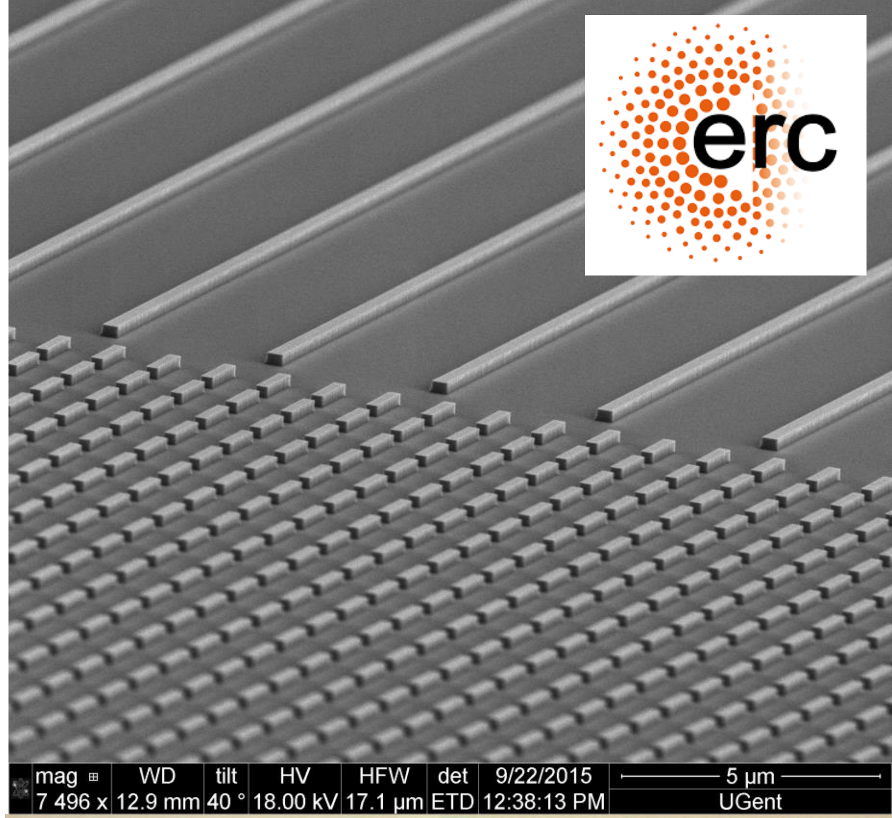
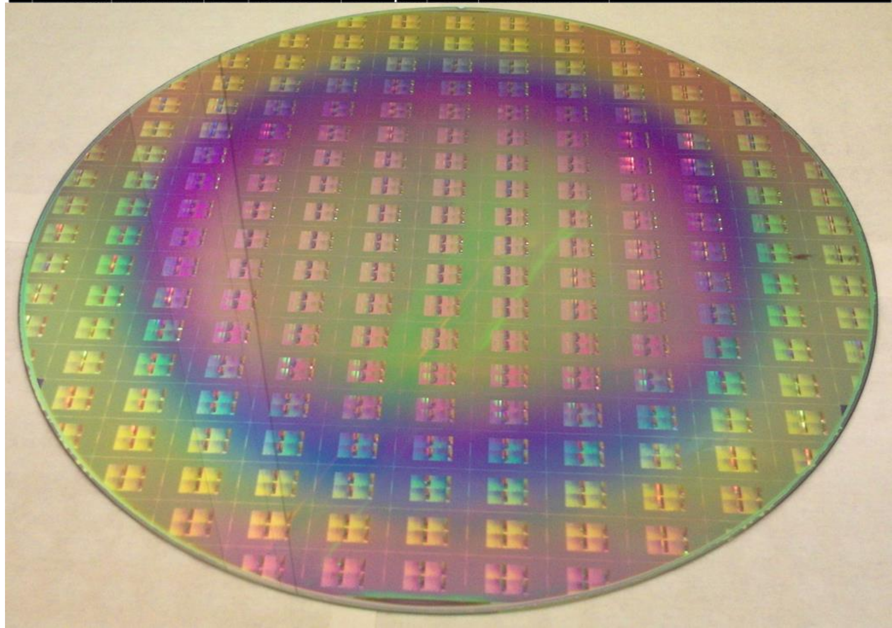
OUTLOOK (EPITAXY)

- Electrical injection ?
- Micro-lasers ?
- Single Photon Emission ?









SUMMARY

SUMMARY & CONCLUSIONS

- Novel materials clearly show prospects for performance beyond what is currently available in existing platforms
  - LN, BTO, PZT high-speed modulators demonstrated by several groups and now in ”spin-off” phase
  - Graphene devices heavily investigated in Graphene Flagship
  - III-V integration through transfer printing and EPI rapidly evolving
- But still a lot of room (and need) for further improvement and research
  - On fundamental building blocks and even materials
  - Towards new applications enabled by these building blocks

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ACKNOWLEDGEMENTS

- UGent Photonics Research Group
- IMEC OIO & EPI teams (J. Van Campenhout, M. Pantouvaki, B. Kunert)
- UGent PCN (Z. Hens, P. Geiregat)
- UGent LCP (J. Beeckman)

- Funding
  - BOF UGent, FWO, EU Commission (ERC, Graphene Flagship, Teraboard, Caladan…)

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EN ARCHITECTUUR

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